Master Thesis

Exploring System Dynamics in Education: A Pilot Study on the Implementation and Impact of Interactive Learning Environments

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Abstract:

This master's thesis explores the potential of Interactive Learning Environments (ILEs) in fostering an understanding of Systems Thinking among high school students, with a specific focus on the context of traffic congestion. Based on foundational theories and methodologies of systems thinking and system dynamics, the study examines the role of ILEs in facilitating comprehension of complex systems. While the results did not clearly demonstrate an enhancement in the understanding of Systems Thinking within the chosen context, the research suggests that ILEs can be both instructive and engaging tools for students, given the right mix of educational content, ILE design and student demographic.

The study emphasizes the importance of User Experience (UX) and Human-Computer Interaction (HCI) in the development of successful ILEs. It also presents challenges in applying ILEs in classrooms, including data collection, theme selection, and demographic considerations. Despite these challenges, valuable insights and recommendations for future research were derived.

This research attempts to contribute to the growing field of study examining the use of ILEs for education purposes. It offers a some understanding of the potential benefits and challenges associated with implementing ILEs in high school classrooms, opening for more nuanced research in the future.

Acknowledgement:

This thesis wouldn't be what it is without the involvement of some truly incredible people, and I want to take a moment to thank them.

First off, my two fantastic supervisors, Saeed Langarudi and Billy Schoenberg, thank you. Your constant encouragement and swift responses kept me motivated and moving forward even on the toughest of days. I'm deeply grateful for your honest feedback and your belief in my potential. Your conviction that I could and should strive for quality has inspired me to give my best.

I would also like to express special appreciation to Ragnhild and Sveinung from Fremtenkt, the enthusiastic high school students who participated in the research, and their dedicated teacher whose assistance was invaluable in facilitating the study.

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A shout-out to my friends and family who've stuck with me. A special mention to my girlfriend, Maria, whose constant encouragement has been my pillar of strength throughout the completion of this thesis and the entirety of the master's program.

As I get ready to start my new chapter at Capgemini, I'm excited to bring all the knowledge I've gathered during these two years.

So, here's to each one of you who've been a part of this journey. From the bottom of my heart, thank you.

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Introduction:

The emergence of computer simulation games and Interactive Learning Environments (ILEs) over the past few decades has significantly influenced educational methodologies, providing innovative ways to facilitate learning and comprehension of complex problems (Alessi & Kopainsky, 2015). The assumption is that these tools, serves as a bridge between theoretical concepts and real-world applications, and therefore increase learners' engagement and understanding of complex systems**.**

Größler and Maier (2000), have made contributions the field. Their work presents a comprehensive classification of computer simulations, offering a set of criteria that distinguish between different types of simulations. This classification system has proven important in understanding the capabilities and limitations of various simulation types, and has guided the development of many simulation tools in the educational domain (Alessi, 2000).

More recent contributions to this sub-field comes from work made by Keith et al. (2017), Abdelgawad et al. (2017), Wong et al. (2018). This and many more (Davidsen & Spector, 2015; Rashidian, 2021; Tadesse, 2019; Fisher, 2023) has brought attention to the critical role of user interaction in learning simulations. Their contributions highlight the importance of gaming-oriented simulations, which emphasize user interaction and incorporate elements of competition or gameplay to facilitate engagement and learning.

Recognizing the increasing need to foster systems thinking among students, this thesis presents a pilot study exploring the potential of an ILE to support the development of systems thinking skills among high school students. The ILE, based on a traffic congestion model, was presented in a high school classroom in Bergen, Norway.

Traffic congestion, a real-world problem with significant social, economic, and environmental impacts, often involves complex systems thinking (Zhang, 2022). Therefore, the aim of this study was to evaluate the effectiveness of the ILE in enhancing high school students' understanding of systems thinking concepts related to traffic congestion, and to identify the key components and features of the ILE that are most effective in supporting high school students' learning and engagement.

The study utilized a mixed-methods approach, using pre-test and post-test measures and in-ILE surveys. The findings from this pilot study can potentially offer valuable insights into the possibilities of ILEs in promoting systems thinking among high school students, and highlight the challenges and limitations of implementing ILEs in a high school classroom setting.

This thesis aspires to add to previous research on the potential of ILEs in facilitating systems thinking education, suggesting that they can provide engaging and interactive learning experiences that enhance students' understanding of complex systems and their interactions (Moxnes, 2004; Moxnes & Jensen, 2008). The findings hope to provide additional literature for future research and development in this scientific area.

Problem Statement:

Systems thinking is a crucial concept that is essential for understanding and navigating the complexities of the world (Meadows, 2008). However, a pervasive lack of understanding of systems thinking among the general population can limit individuals' ability to think critically and creatively about complex systems and their interactions (Richmond, 1993; Sterman, 2000). This deficit also hinders the learning and comprehension of global complexities (Forrester, 1994).

Given these challenges, there is a growing interest in understanding how Interactive Learning Environments (ILEs) can be designed and implemented to support the development of systems thinking skills (Alessi & Kopainsky, 2015; Rashidian, 2021). Education plays a pivotal role in equipping future generations with the necessary tools to comprehend and address the complexities of the world.

ILEs have demonstrated significant potential in this process. By providing a dynamic and engaging learning experience, ILEs enable students and other learners to explore and experiment with complex systems within a controlled and safe environment (Spector, 2014). This facilitates the development of systems thinking skills and improves students' understanding of the complexities of the world (Sweeney & Sterman, 2007). With the aim of further enriching this educational approach, this study will focus on the use of an ILE designed to enhance understanding of traffic congestion, a complex real-world system (Zhang, 2022).

Despite the potential benefits of ILEs, existing research on their effectiveness in supporting the development of systems thinking skills among high school students has the potential to grow (Alessi, 2000; Größler & Maier, 2000; Rashidian, 2021; Moxnes & Jensen, 2009; Moxnes et al., 2003; Kopainsky & Sawicka, 2011). Moreover, literature offers general guidelines on designing and implementing ILEs that can effectively foster systems thinking skills (Forrester 2007; Arndt, 2006).

In response to this, this study sets out to develop, implement, and evaluate an ILE rooted in a traffic congestion model based on the existing literature. The aim is to use this ILE in a high school classroom setting to introduce students to systems thinking concepts. The selection of Bergen, Norway as the study context provides a pertinent platform for investigating issues related to traffic congestion. Historically, Bergen has consistently addressed its traffic challenges through the construction of additional roadways, particularly during the 1960s through the 1990s. This approach has inadvertently resulted in numerous ecological and societal challenges. Specifically, the urban expansion has led to the reduction of green spaces, augmentation of the city's carbon footprint, and degradation of air quality (Eriksen, 2020; Eriksen, 2023). The present research aims to examine the traffic situation in Bergen, as it serves as a representative case study in the context of sustainable urban planning.

Research Questions:

The purpose of this study is to explore the potential of Interactive Learning Environments (ILEs) in promoting systems thinking among high school students. The specific focus is on a traffic congestion model, a complex real-world system that requires systems thinking to understand and address effectively (Zhang, 2022). This study is grounded by three core research questions:

1. **To what extent does the use of an Interactive Learning Environment (ILE) influence high school students' understanding of systems thinking concepts related to traffic congestion?**

This question seeks to evaluate the impact of the ILE on enhancing high school students' comprehension of systems thinking, specifically the role of feedback within the context of traffic congestion in Bergen Norway.

2. **Does a traffic congestion-themed ILE effectively introduce high school students to the concept of feedback loops?**

This question examines whether a traffic congestion-themed ILE effectively introduces feedback loops to high school students, presuming their initial understanding of the theme is minimal.

3. **What are the challenges and limitations of implementing ILEs in a high school classroom setting, as reported by the researcher?**

This final question will explore potential obstacles and limitations of integrating ILEs like the traffic congestion game into a high school classroom from the perspective of the researcher.

Through these research questions, this study aims to contribute to the broader discourse on ILEs and systems thinking education. The insights derived from answering these questions will inform the design and implementation of similar educational interventions in the future. Generally, the objective is to develop effective strategies and tools for enhancing systems thinking skills among high school students.

Literature Review:

Background:

Building on the introduction's discussion of the educational potential of Interactive Learning Environments (ILEs) in developing systems thinking skills among high school students, this literature review goes deeper into the theoretical and practical aspects of this topic. It provides an overview of the foundational theories and methodologies related to systems thinking and system dynamics, and further discusses the application and effectiveness of ILEs in facilitating a deeper understanding of complex systems. By dissecting these components, this literature review aims to establish a strong theoretical foundation for the research questions outlined previously, bridging the gap between the broader context provided in the introduction and the focused empirical investigation that follows.

System Dynamics and Systems Thinking:

Systems thinking and system dynamics are closely related fields that share a common focus on the study of complex systems and their behavior over time (Forrester, 1961; Sterman, 2000). While both fields have their roots in the work of Jay Forrester and others in the mid-20th century, there are some key differences that set them apart.

Systems thinking is a wide approach to problem-solving that focuses on the interconnections and interactions between different elements of a system, rather than on the individual components in isolation (Senge, 2006). It is based on the idea that a system is more than the sum of its parts, and that understanding the relationships and dynamics between the parts is essential for understanding the behavior of the system (Meadows, 2008). Systems thinking is concerned with understanding how systems evolve and change over time, and how they can be influenced and managed to achieve desired outcomes (Forrester, 1994).

System dynamics, on the other hand, is a more specific methodology for modelling and simulating the behavior of complex systems over time in terms of system feedback (Forrester, 1961). It is based on the use of graphical models and computer simulations to represent the relationships and dynamics between the different elements of a system, and to explore the implications of different assumptions and scenarios. System dynamics is particularly useful for analyzing feedback loops and nonlinearities in systems, and for understanding how minor changes can lead to large and sometimes unexpected outcomes (Barlas, 1996).

System Dynamics (SD) is a robust approach for understanding the behavior of complex systems over time (Forrester, 1961). It uses feedback loops, stocks and flows, and time delays to model complex interactions and dynamics. SD is particularly useful in addressing socio-economic and environmental problems, which are often characterized by complexity and interconnectedness (Forrester, 1999).

Studies within System Dynamics have demonstrated its capability in analyzing and making sense of complex systems. These systems span a variety of fields including health systems enhancement, as outlined by Hirsch et al. (2012), the comprehension of environmental problems as depicted by Ford (1999), as well as transdisciplinary and globally recognized works like Limits to Growth, authored by Meadows et al. in 1972 and updated in 2004.

More recent and topical work (for the thesis) shows that SD models can be instrumental in supporting decision-making processes (Keith, Naumov & Sterman, 2017). In their study, a model of the US Automobile Market was designed, illustrating how SD can provide insights into the interdependencies of several factors affecting the market.

Hopper & Stave (2008) investigated the application of system dynamics (SD) in educational contexts, highlighting the potential benefits and obstacles associated with introducing systems thinking strategies in the classroom. They emphasized that the aim should be to foster systems thinking capabilities among students rather than attempting to transform all users into system dynamics practitioners. They underscored the integrative nature of the SD approach, its promotion of active learning, and its potential to enhance students' critical thinking and critical thinking skills. They also highlighted the need for more rigorous analysis in this domain, pointing to the necessity for robust evaluation methods.

The assessment of systems thinking skills is a relevant issue in communicating SD concepts (Arndt, 2006). Hopper & Stave (2008) listed a variety of methods for evaluating various aspects of systems thinking, such as identifying relationships and feedback, understanding dynamic behavior, and using conceptual models. They also noted that the tests created by Sweeney and Sterman (2000) to explore students' baseline systems thinking abilities have received criticism and might not be applicable in all situations.

However, despite the challenges, the benefits of applying SD in educational settings are clear. For instance, Hopper & Stave (2008) identified seven characteristics for systems thinking, highlighting the multifaceted nature of this approach. This makes SD a versatile tool for teaching students to think in terms of systems, whether in the context of environmental issues, socio-economic problems, or other complex scenarios. This adaptability is supported by many examples, as demonstrated in the body of work by the Creative Learning Exchange (Benson et al., 2015; LaVigne et al., 2010), strengthening the application of SD in diverse contexts.

In line with this, recent contributions in the field, including the projects conducted by Strohhecker & Größler (2015), Fischer, Degen & Funke (2015), and Stave, Beck & Galvan (2015), as well as the academic work by Tadesse & Davidsen (2019) and Rashidian (2021), further demonstrate the broad applications and continued interest in SD research. These works contribute to the growing body of literature emphasizing the value of SD as a method for understanding and addressing complex problems, both in educational settings and beyond.

Interactive Learning Environments

Interactive Learning Environments (ILEs) have emerged as a powerful tool to facilitate the understanding of complex system dynamics (SD) concepts. The interactive nature of ILEs serves to engage users more actively in the learning process, enabling the application of theoretical knowledge to practical scenarios (Davidsen & Spector, 2015).

ILEs often employ simulation models to provide a tangible experience of SD concepts. As Stave and Hopper (2008) noted, the ability to manipulate various parameters within a model allows learners to grasp the non-linearities and feedback loops inherent in complex systems. This, in turn, promotes a more profound understanding of the implications of decision-making within such systems.

The effectiveness of ILEs in promoting learning is well-documented. A study conducted by Keith, Naumov & Sterman (2017) highlighted the role of ILEs in improving mental models and decision-making. The authors described the development of a management flight simulator, Driving the Future (DtF), which allowed participants to interactively explore scenarios and make decisions that would influence the outcomes within a simulation of the US automobile market. The study found that participants who interacted with the simulator showed measurable learning, further demonstrating the effectiveness of ILEs. Humphreys et al. (2016) have also garnered praise for their efforts in related research.

It is also worth noting that the concept of interactive simulation-based learning extends beyond academia and is seen in mainstream entertainment, with certain video games serving as good examples. For instance, Sim City, an Urban Planning Simulator (Yasin et al., 2022), and Europa Universalis, a Nation-builder Simulation (Loban, 2021), stand as popular examples. Within business management, simulation-based learning is most known by the work of the Harvard Business School, such as their work with the Global Supply Chain Simulation (Hammond, 2016). Despite the diversity in these and other examples, the common factor is the collective spotlight on the potential interactive simulations hold in enhancing the understanding of system, complex problems or for double loop learning.

The adaptability of ILEs to various contexts is another of their strengths. ILEs can be designed to cater to various learning goals and various levels of complexity. This flexibility makes them an ideal tool for teaching SD concepts to a diverse range of learners, from high school students to professionals (Hopper & Stave, 2008).

The use of ILEs in a classroom setting can also be beneficial for teachers. As noted by Hopper & Stave (2008), implementing ILEs in the classroom could stimulate active learning and help students develop critical thinking and problem-solving skills. Moreover, the use of ILEs provides an opportunity for teachers to assess students' understanding of SD concepts through their interactions with the simulator.

However, like the implementation of SD in educational settings, the use of ILEs is not without challenges. Ensuring that the learning environment is user-friendly and intuitive is crucial to the successful implementation of ILEs. As highlighted by Keith, Naumov & Sterman (2017), the design of the user interface is a crucial factor in engaging users and facilitating their interaction with the ILE.

Human Computer Interaction and UX:

User experience (UX) is a critical element in the development of effective Interactive Learning Environments (ILEs) for system dynamics education. An understanding of UX principles and how they apply to the design and implementation of ILEs is vital to creating an engaging and intuitive interface that facilitates learning and understanding of complex system dynamics concepts (Nielsen, 1993; Hartson & Pyla, 2012).

UX entails the user's entire interaction with the ILE, including their emotional responses, perceptions, and physical and psychological engagement with the interface. It goes beyond the mere functionality and ease of use (usability) to include the overall satisfaction, enjoyment, and value that the user gathers from the interaction (Preece, Rogers, & Sharp, 2015).

The design of ILEs in system dynamics should prioritize both usability and user experience. A high level of usability allows users to navigate the ILE easily and understand how to manipulate system components within the simulator (Qudrat-Ullah, 2010). Meanwhile, a positive user experience encourages active engagement, promotes deep understanding, and motivates continued learning.

The design of the ILE interface plays a substantial role in shaping the user experience. As Keith, Naumov & Sterman (2017) demonstrated in their development of the Driving the Future (DtF) simulator, a well-designed user interface provides clear visual representations of system components and relationships, enabling users to quickly grasp the layout and functionality. The interface should also offer tools for manipulating these elements, allowing users to experiment with different scenarios and observe the effects of changes within the system.

Interactivity is another crucial aspect of user experience. Interactive elements in an ILE allow users to actively engage with the learning material, promoting a deeper understanding of complex system behaviors and concepts such as feedback loops and time delays. However, the level of interactivity should strike a balance between engagement and manageability to ensure users remain engaged without becoming overwhelmed or frustrated (Sweeney & Sterman, 2000; Kopainsky et al., 2011).

Data visualization, the graphical representation of information and data, is a critical component of UX, particularly in the context of ILEs used for system dynamics education. The presentation of complex, dynamic systems in a visually intuitive and engaging manner plays a significant role in shaping the overall user experience (Card, Mackinlay, & Shneiderman, 1999).

The effective use of data visualization techniques can substantially enhance the usability of an ILE. For instance, presenting system components and their relationships through well-designed diagrams, graphs, and other visual elements can greatly facilitate users' understanding of the system's structure and behavior (Keith, Naumov & Sterman, 2017). Similarly, visualizations of system outputs—such as behavior over time graphs—can provide users with immediate, intuitive feedback on the impacts of their actions within the simulator, thereby promoting a deeper understanding of system dynamics principles (Sterman, 2000).

Moreover, data visualization contributes to an engaging user experience. A visually appealing interface can stimulate users' interest and enjoyment, thereby motivating sustained engagement with the ILE. Interactive data visualizations can encourage active exploration and experimentation, allowing users to gain a deeper, experiential understanding of complex system behaviors (Heer, Bostock, & Ogievetsky, 2010).

However, the design of data visualizations in ILEs also presents challenges. It is crucial to present complex data in a manner that is both comprehensible and not overwhelming to users. This requires careful consideration of various design factors, including the choice of visualization type, the use of color and scale, and the degree of interactivity. Furthermore, designers must ensure that the visualizations align with the learners' pre-existing knowledge and cognitive abilities to facilitate effective learning (Tufte, 2013).

Relevance of study:

This study, while modest in its scope, aims to provide some contribution to the transdisciplinary fields of systems thinking and system dynamics, Interactive Learning Environments (ILEs), Education and User Experience (UX) design. Although it is a small piece in the larger puzzle of modern education, the study's relevance is grounded in several key areas:

Promoting Systems Thinking Skills: Systems thinking is an increasingly valued skill in our complex world, and the study aims to further the discourse on nurturing this skill among high school students. By evaluating the potential of the traffic game to fostering systems thinking skills, the study hopes to add some insights to this important aspect of education.

Informing UX Design for System Dynamics Communication: Moreover, this study steps into the intersection of UX design and ILE development. By cautiously investigating how UX design principles may potentially augment the usability and effectiveness of ILEs (using the traffic game as a case study) in the context of systems thinking education, it hopes to provide a few insights that could guide future design considerations. This could influence the way system dynamics insights are communicated to those who may not be deeply entrenched in the field.

Facilitating Decision-Making: Existing literature has highlighted the role of system dynamics models in aiding decision-making processes (Keith, Naumov & Sterman, 2017). This study hopes to build upon these findings and contribute in some way to this ongoing discourse.

While the study does not claim to revolutionize any field, it hopes to shed some light on the potential of ILEs to foster systems thinking skills among high school students and offer some insights into UX design in ILE development. Its aim is to provide some useful insights that might help to aid future research within SD and ST understanding and ILE development.

Methodology:

Overview:

This study utilized a three-phase, mixed-method approach. The first phase involved creating a system dynamics simulation model that depicted traffic congestion and its influencing factors, including feedback loops. The second phase entailed designing an Interactive Learning Environment (ILE) based on this model, aimed at increasing high school students' understanding of the complexity of traffic congestion. Additionally, it served to either expand their existing understanding or to introduce them to system thinking and feedback loops. The final phase was a pilot study involving pre- and post-tests, reflective journals to assess the ILE's effectiveness in enhancing students' understanding of feedback loops. This pilot study, conducted in a high school setting with approximately 10 participants, allowed for an evaluation of the ILE's impact on the students' learning experiences.

Phase 1: Model Development and Validation:

Development:

The master's thesis introduced the model that served as the foundation for the Interactive Learning Environment (ILE) used in the pilot study. The ILE was based on a model obtained from isee Exchange and which is developed by isee systems ("Systems in Focus – Transportation," n.d.).

The base model is a three-stock system that primarily focuses on how the connection of population increase and road construction affect traffic congestion. Road construction is driven by the road gap, which emerges because of congestion. When congestion is high, the road gap widens, indicating an increased need for roads. However, since road construction takes time and the population continues to grow, as evidenced by the population increase stock-and-flow system, congestion levels persist despite the construction of additional road kilometers. The base model effectively illustrates the thought process of stakeholders when planning for road expansion (Model 1). It uses the principles of traffic congestion modelling, as elaborated in recent studies by Su et al. (2020) and Zhan (2022). Additionally, it implements the use of local-context ILEs to create a deeper understanding of sustainable decision-making, a strategy presented in research of Stave (2002).

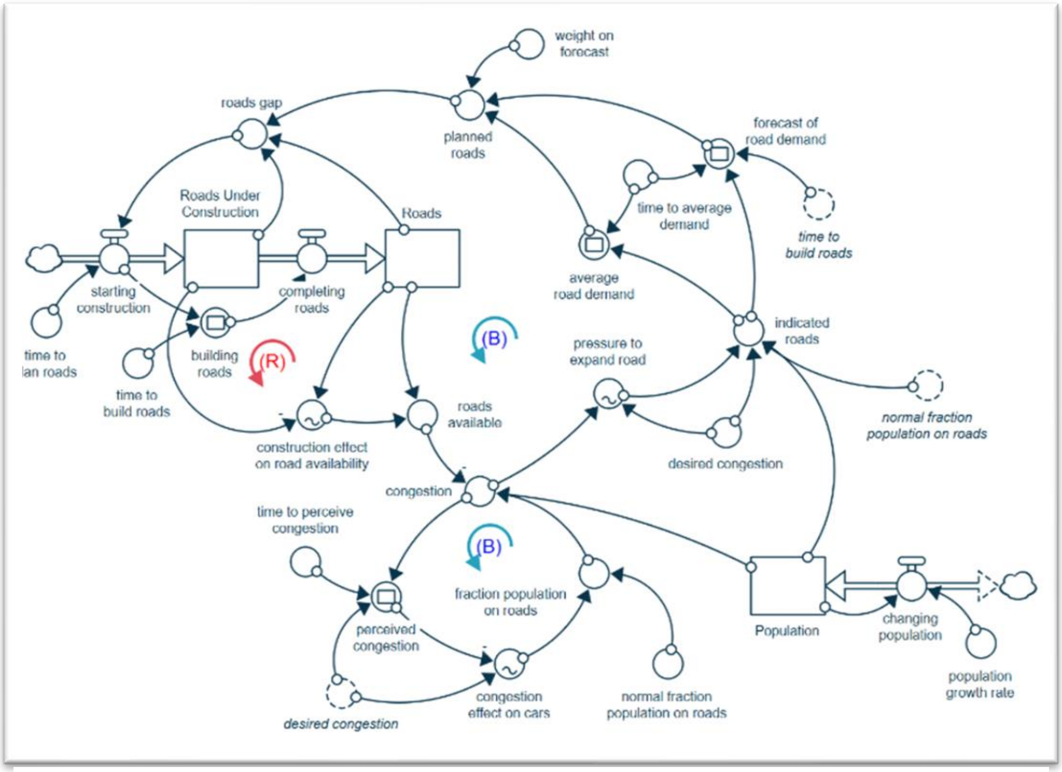


Figure 1 – The Base Model as gathered from the isee exchange

The original model offers limited opportunities for intervention; thus, it was necessary to incorporate additional structure to enable its possibility of intervention. One approach to counter the reinforcing feedback loop of road construction is to promote public transport usage (Nguyen-Phuoc et al., 2020). The assumption is that a fully occupied bus can replace up to 30 cars, assuming each car has 1.5 passengers, and therefore reducing the number of vehicles on the road helped prevent congestion from escalating (Buses, 2022). The added structure implements a bus-system which reacts to changes in congestion. The bus-structure is co-developed by me and Henri Contor in a previous project (GEO-SD325). The enhanced structure allowed users of the ILE, acting as decision-makers, to observe the impact of investing in public transport as an alternative to pursuing car-centric policies. A more detailed description of the model is presented in the appendix (Appendix 1).

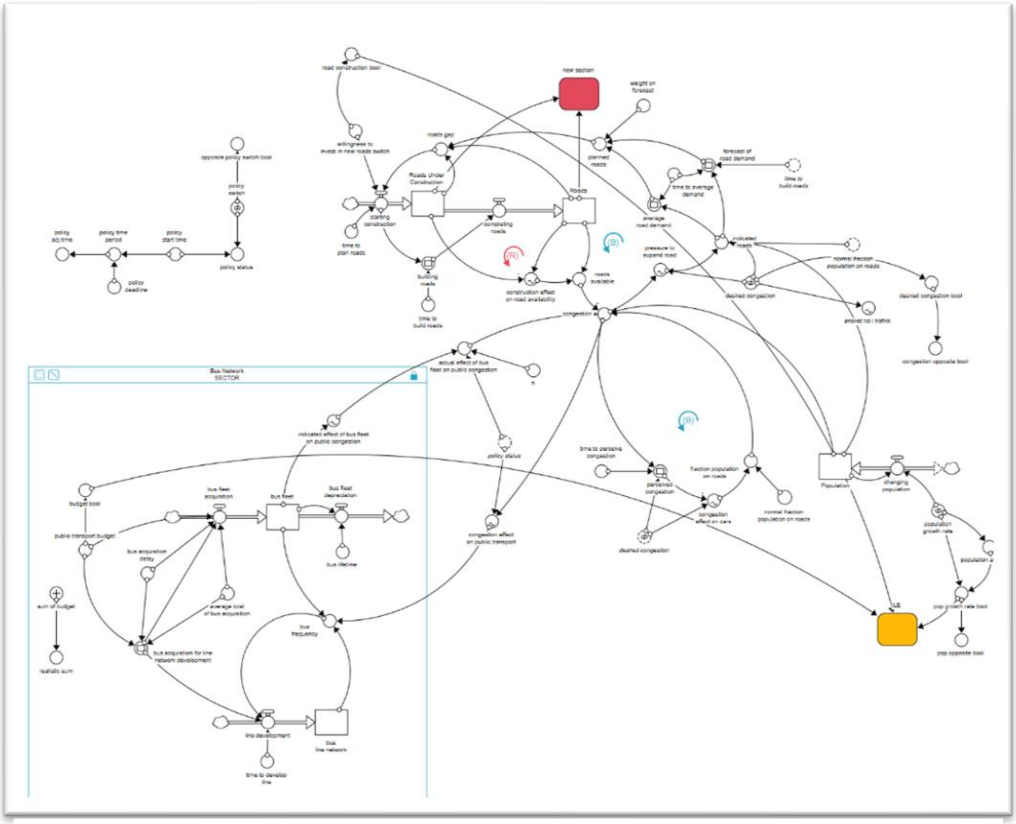


Figure 2 - An altered version of the traffic congestion model gathered from the isee exchange

Validation:

Model validation, according to Schwaninger and Grösser (2020), is an integral and pervasive aspect of model building. It serves as a control function to ensure the model's realism, reducing cognitive limitations and modeler biases, thereby aiding in the creation of a more realistic representations of the system under study, while continually validating the model using diverse tests. Even in ILEs, where emphasis is on intuitive understanding rather than precise simulation, validation remains significant (Schwaninger & Grösser, 2020). This thesis selectively performs a sensitivity analysis and extreme conditions test, considering the educational context of the ILE, to provide insights into the model's performance, ensuring a realistic representation of the studied system dynamics.

Behavior Sensitivity Test:

Sensitivity analysis is a crucial method in system dynamics, enabling a comprehensive assessment of a model's robustness in terms of its inputs influencing its outputs. As outlined by Sterman (2000), sensitivity analysis probes the numerical, behavioral, and policy sensitivity of a model by tweaking parameters, boundaries, and aggregation over a range considered plausible. In this chapter, the focus lies on the sensitivity analysis of three adjustable parameters from the pilot study, namely: Desired Congestion, Public Transport Budget, and Population Growth Rate. These three parameters were selected for their role as policy variables directly manipulated by the user.

For each parameter, the values were varied across a range matching the input range available to users in the ILE interface. Then, the changes were observed in output metrics under these variations. This approach helped to understand the model's sensitivity to these policy variables. Moreover, it facilitated the evaluation of the model's fitness for purpose, i.e., its usability in the ILE.

The analysis demonstrated varied sensitivities of the model to changes in the chosen parameters. Desired congestion, when altered, reversely affected the number of roads (Figure 1). Despite this, the bus fleet variable remains constant (Figure 2). While the bus line network variable could seem constant at first, it exhibits linear variability depending on the desired congestion levels (Figure 3).

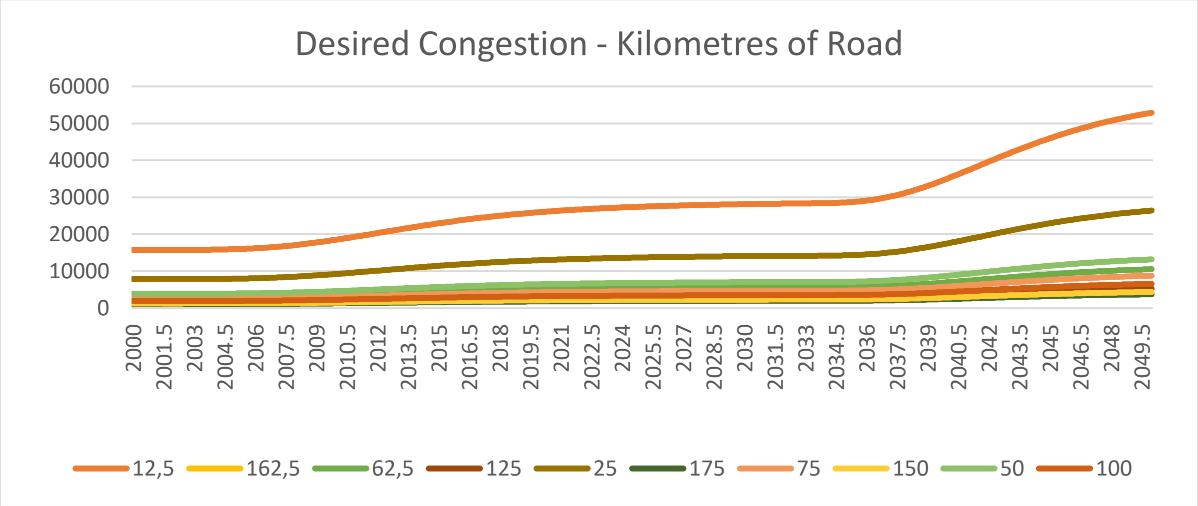
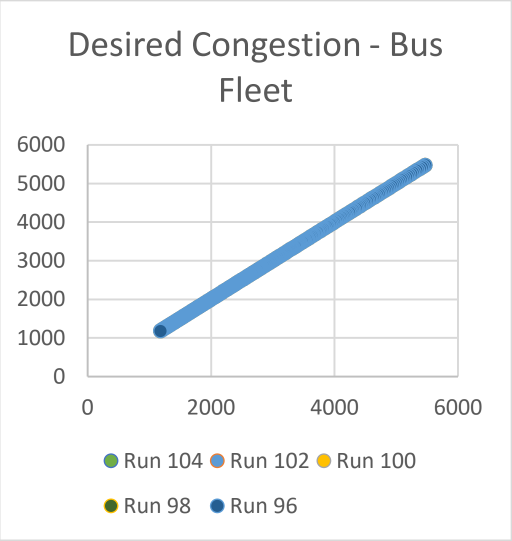


Figure 3 – Desired Congestion input on Kilometres of Road output – the colors presents different values as presented above



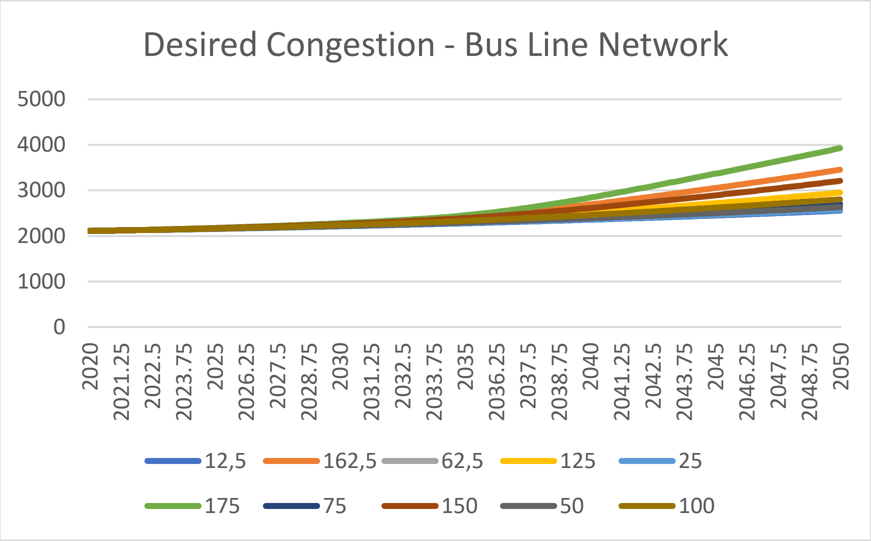


Figure 4 – Desired Congestion input effect on Bus Line Network output: Bus Fleet remains constant despite change in variable.

Figure 5 – Desired Congestion Input effect on Bus Line Network Output: Exhibits Linear Variability in the last 30 years of the simulation time.

A sensitive effect was observed when manipulating the public transport budget. Initially, higher budgets led to an increase in roads under construction. However, after reaching a certain threshold, the number of roads under construction declined significantly. The expansion of the bus line network and bus fleet consistently correlated with increased budgets. Furthermore, congestion levels showed a non-linear response, stabilizing beyond a specific budget point (Figure 4). This suggests that substantial investment in public transport is required to achieve a lasting reduction in traffic congestion.

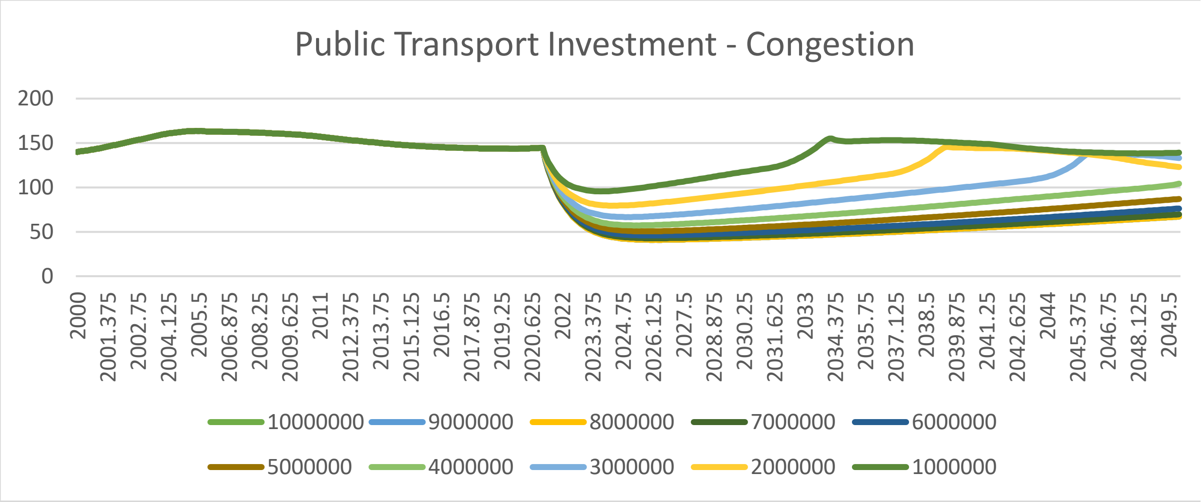


Figure 6 – Public Transport Investment effect on Congestion

Lastly, the model demonstrated high sensitivity to population growth rate changes. As growth rate increased, expectably the population grew, but so did number of roads under construction, total roads, and the bus line network size (Figure 5 and 6). Congestion showed an interesting pattern, decreasing initially with population growth and then increasing, suggesting a delayed system response. The bus fleet size, however, remained constant, pointing to weaknesses in the model. The model's insensitivity to population growth in relation to bus fleet size exposes a critical flaw. Realistically, a larger population should lead to an expanded bus fleet to meet growing public transport needs. This oversight could misrepresent congestion predictions and policy effectiveness.

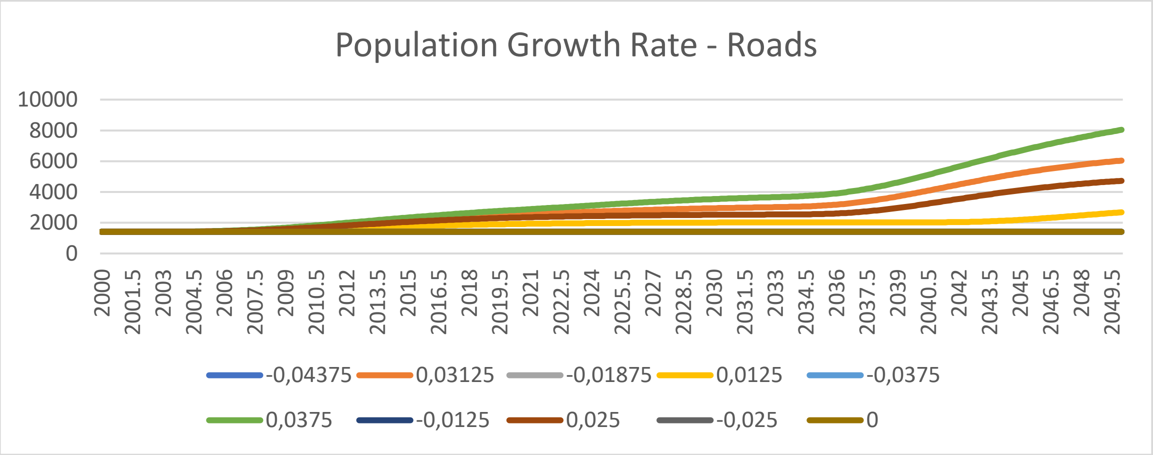


Figure 7 – Population Growth Rate effect on Number of Roads

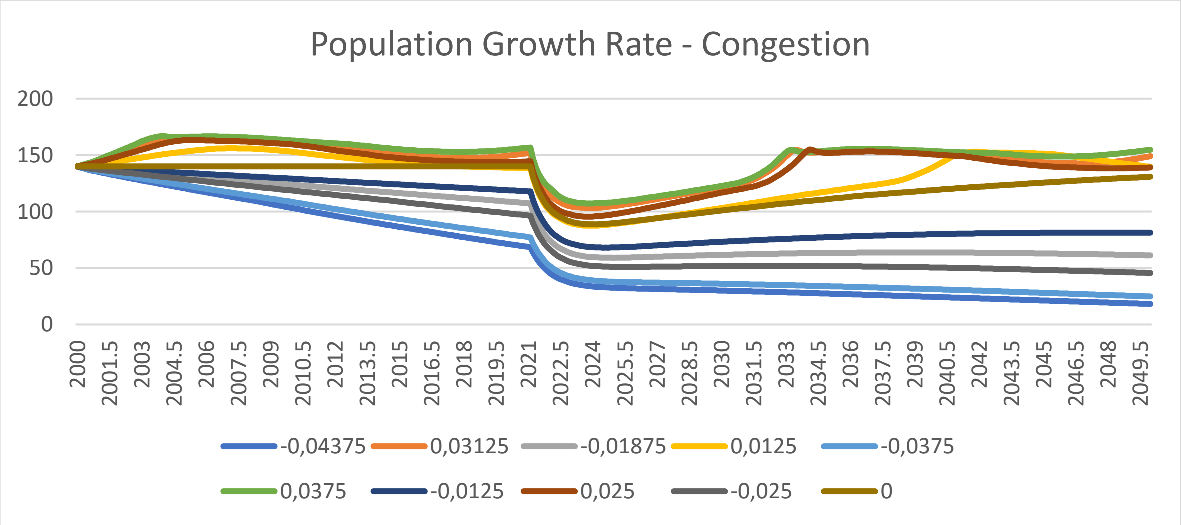


Figure 8 – Population Growth Rate effect on Congestion

The multivariate sensitivity analysis aimed to examine the model's response to simultaneous variations in the parameters: Population Growth Rate, Desired Congestion, and Public Transport Budget. The analysis involved a series of runs with different combinations of the three parameters (Appendix B) focusing on the effect these changes had on the population count in different years.

The multivariate sensitivity analysis provides important insights into how the model responds to simultaneous changes in different parameters, in this case, Population Growth Rate, Desired Congestion, and Public Transport Budget. In this analysis, one significant finding is associated with Run #25, which combines a moderate Population Growth Rate of 0.01565(per year), the lowest value of Desired Congestion (6.25 people per lane kilometer), and the value of Public Transport Investment being 5 million (EUR/year).

This specific run stands out as an outlier, yielding the highest output for the stock of Kilometres of Roads (Figure 7). The unusually high output appears to be predominantly influenced by the very low Desired Congestion level, with the relatively high Population Growth Rate amplifying this effect.

On the other end of the spectrum, Run #30, which has the lowest Population Growth Rate, the third highest Desired Congestion rate, and the highest Public Transport Budget of 10 million, results in the lowest output value for the Kilometres of Roads.

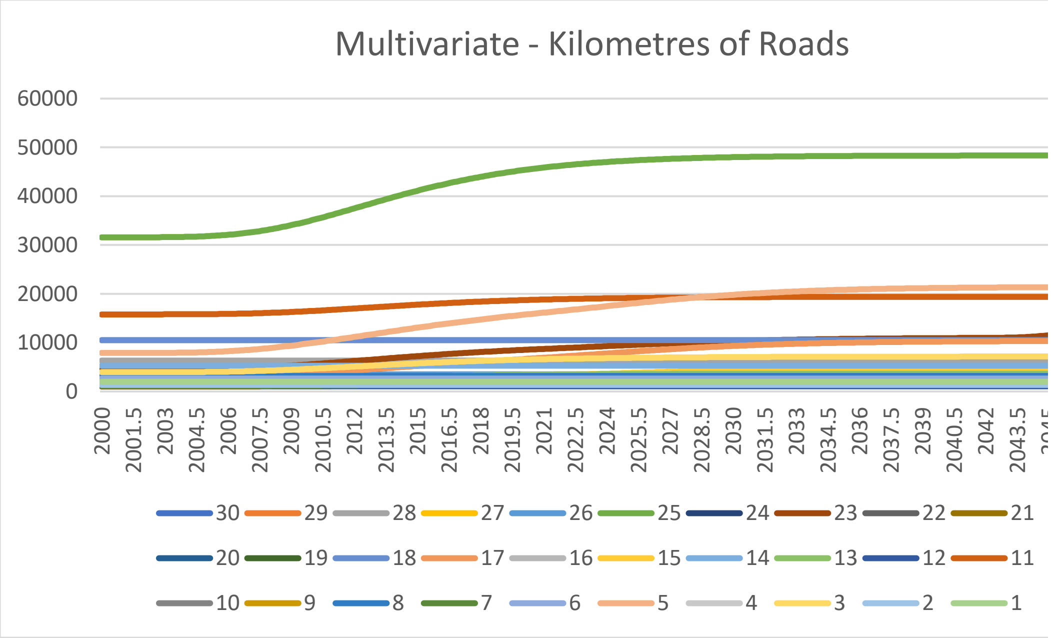


Figure 9 – Multivariate Analysis effect on Kilometres of Road

Extreme Condition Testing:

Extreme condition testing is a crucial aspect of system dynamics validation, allowing us to understand the model's behavior under atypical and exceptional, but possible real-world scenarios (Sterman, 2000; Schwaninger & Grösser, 2020).

The model demonstrates a relative robustness under extreme conditions with the adjustment of the parameters of desired congestion, public transport budget, and population growth rate. These parameters are chosen as they are the parameters that participants can influence in the ILE. The model balances infrastructure development with desired congestion levels, and shifts priorities from road construction to public transport as budget increases. These behaviors reflect a strong congruence with anticipated real-world responses.

However, the model shows weaknesses. Despite extreme variations in desired congestion and public transport budget, certain parameters like bus line network, bus fleet remain constant even though it is circularly connected to the remaining structure. Moreover, the model maintains a constant bus fleet size across all population growth rates, disregarding this crucial parameter. These instances suggest potential areas for refinement.

Reflection on Validation

Validation of system dynamics models is a crucial part of ensuring their credibility and robustness (Sterman, 2000). In this study, the model's structures have been superficially tested through sensitivity analysis and extreme condition testing. These tests were instrumental in identifying the strengths and weaknesses of the model in reflecting the dynamics of urban transportation.

Extreme condition testing has helped to identify a set of structures which when subjected to extreme conditions perform adequately. The most convincing among these is the nuanced response to increasing population levels. As the population growth rate increases, the model exhibits an expected escalation in the number of roads under construction. This demonstrates that the system is adapting to the increased demand, thereby managing to maintain relative stability in congestion levels despite a booming population. Even though this is not a desirable income in terms of sustainability as it leads to more road building, it shows that the model works as intended. This aspect of the model displays a solid understanding of the real-world dynamics between population growth, road infrastructure development, and traffic congestion (Sterman, 2000).

However, extreme conditions testing has identified some weaknesses in model structure. Specifically, the Bus Fleet and Bus Line Network variables of the model remain constant when desired congestion levels, population growth rates, and public transport budgets are adjusted. Realistically, these parameters should exhibit significant changes in response to varying congestion levels, population growth rates, and public transport budgets. However, they do not, which is an indication of overly simplistic modeling in these areas (Schwaninger & Grösser, 2020).

Despite these known issues, the model was deemed fit for purpose for use in this ILE because changes in Bus Line Network and Bus Fleet due to changes in the policy parameters (Desired Congestion, Public Transport Investment, and Population Growth Rate) are not critical to learning feedback loops in the context of traffic congestion in Bergen.

Phase 2: ILE Design and Development:

The creation of the Interactive Learning Environment (ILE) was guided by the prevailing issue of traffic congestion, using the city of Bergen, Norway as a practical example. The decision to ground the simulation in a specific city, even though historical data was not used, was influenced by a desire to boost student engagement. This engagement strategy, rooted in creating a relatable context, is a key component of positive User Experience (UX), which goes beyond mere usability to encompass the emotional and psychological involvement of the user (Preece, Rogers, & Sharp, 2015).

The introduction of the ILE was designed with a modern, minimalist aesthetic and a user-friendly interface to ensure an intuitive and visually pleasing initial interaction. This decision was made based on principles of UX, which emphasize the role of aesthetics and intuitive design in creating an engaging and satisfying user experience (Nielsen, 1993; Hartson & Pyla, 2012).

Hei og velkommen til deltakelse på dette forskningsprosjektet!

Takk for den innsatsen dere allerde har lagt inn i prosjektet ved å svare på spørreundersøkelsen dere fikk i forrige time.

Dere bruker nå det som kalles et interaktivt læringsverktøy. Hensikten med forskningsprosjektet er å finne ut av om dere vil øke forståelsen deres av bærekrafts- og beslutningstakingsproblemer ved å navigere dere gjennom dette verktøyet.

For å gå videre må du fylle ut ID-nummeret. Dersom det er riktig vil det dukke opp en knapp som tar deg videre til neste side.

Fyll inn utgitt ID nummer: 0

ILE Slide 1 – Introduction

Introduksjon

ID-nummer: 0

For at dere skal få en så god opplevelse som mulig, vil vi først forklare hvordan (dette interaktive lærings)verktøyet fungerer.

Trykk på knappen under for å komme videre til neste steg.

ILE Slide 2 – Navigation guide

Ensuring seamless navigation was a priority in the design process, as poor navigability can negatively impact usability and, by extension, the overall user experience. Therefore, a navigation guide was provided at the outset, and the students' unique ID was used as a tool to personalize the experience and track progression through the ILE.

The interactive components were introduced early on to promote active learning and immediate engagement with the model's theme. The pedagogical principle of active learning inspired this design choice, highlighting the importance of interactivity in shaping a positive and engaging user experience (Sweeney & Sterman, 2000). In the two first interactive tasks the participants are meant to guess the biggest sources for emissions in Bergen (ILE Slide 3) and the size of the different car parks respectively. After each interactive task they are given the results and the historical data spanning from 2008 to 2021 (ILE Slide 4).

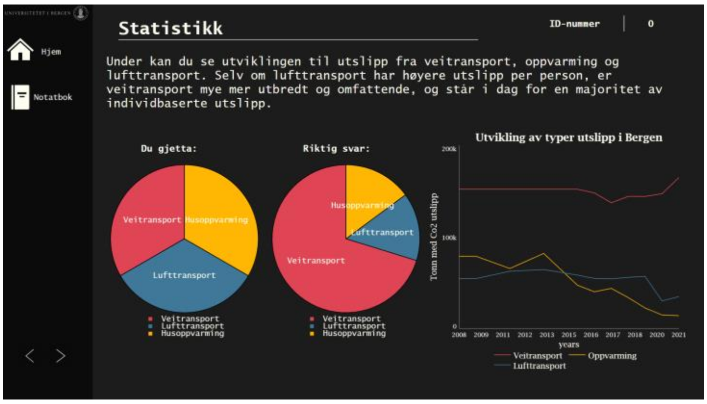
Statistikk

ID-nummer | 555

Du som beslutningstaker skal jobbe for å redusere utslipp, men da er det greit å vite hva det er som bidrar til mest utslipp i nærområdet ditt. Først ut er individbaserte CO2-utslipp.

Bruk det interaktive kakediagrammet under til å anslå hva du tror har de største utslippene i dag. På neste side vil du få se fasiten.

ILE Slide 3 – First Interactive Task: Which of the three sources of emissions (road transport, air transport, and heating) emits the most.



Statistikk

ID-nummer | 0

Under kan du se utviklingen til utslipp fra veitransport, oppvarming og lufttransport. Selv om lufttransport har høyere utslipp per person, er veitransport mye mer utbredt og omfattende, og står i dag for en majoritet av individbaserte utslipp.

ILE Slide 4 – Solution of first interactive section – also shows the historical data over the last 15 years.

After the initial interactive component, users are prompted to complete a reflection journal entry. In the first reflection journal, the participants are asked five questions (Table 4).

Reflection Journal 1:
In the first interactive task, you were supposed to figure out the distribution of individual-based CO2 emissions in the Bergen region. Did the solution surprise you? If yes, what was surprising? If no, what made you aware of it beforehand?
Road transport is the largest source of CO2 emissions in the Bergen region. Can you think of policies that could be designed to address this problem?
In the second part of the interactive task, you were supposed to figure out what the distribution of the car fleet looks like in Bergen. Did the solution surprise you? In other words, that there is an approximately equal distribution of the different types of cars? If yes, why? If no, why not?
Road transport is the largest source of CO2 emissions in the Bergen region, and we have seen that an increasing number of new cars are electric. Do you believe that a continuing increase in the electric vehicle fleet is sufficient to solve road traffic problems in Bergen? If yes, why are other strategies necessary in addition to a green car fleet?

Table 1 – The first reflection journal.

The inclusion of reflective exercises was influenced by the understanding that reflection enhances learning by solidifying knowledge and fostering deeper insights (Qudrat-Ullah, 2010).

Dynamiske ringvirkninger

Frem til nå har du fått se at biltrafikk medfører en del utslipp, men allikevel er vi helt avhengige av transport med enten bil, buss eller bane for å komme oss rundt i hverdagen. For å forstå kompleksiteten i dynamiske systemer kan det være greit å være obs på såkalte feedback loops eller dynamiske ringvirkninger.

En dynamisk ringvirkning oppstår når utfallet av en prosess påvirker prosessen. Tenk at du skal presentere et prosjekt i klassen, og kjenner deg nervøs. Fordi du er nervøs, glemmer du hva du skal si. Det gjør deg enda mer nervøs, som gjør at presentasjonen går helt i stå. Det omvendte kan også skje: du er nervøs, men husker hva du skal si. Det gjør deg mindre nervøs, som igjen gjør at presentasjonen flyter bedre. Dette er eksempler på dynamiske ringvirkninger.

ILE Slide 5 – Introducing the theme of traffic congestion.

Dynamiske ringvirkninger

Et annet eksempel på en slik dynamisk ringvirkning er hvordan beslutninger blir tatt når en kommune / fylkeskommune skal bygge ut veier. Det er kø på veiene, og siden det er kø, blir det bestemt at det skal bygges flere og/eller bredere veier. Det tar tid å planlegge og lage vei og det blir som regel estimert etter datidens befolkning. Rett etter veien er ferdig blir det kortere kø. Siden bilkjøring blir lettere velger flere bilen , og siden flere kjører blir tiden i kø omtrent lik som den var før.

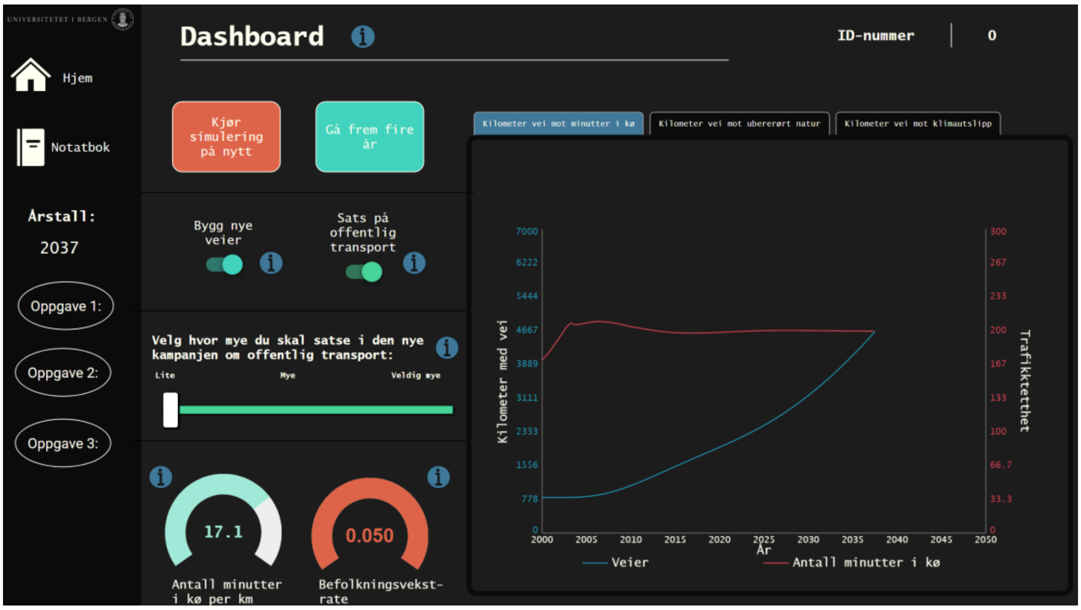
Se dette i illustrasjonen under:

I neste del skal dere selv få muligheten til å påvirke dette systemet.

ILE Slide 6 Introducing the concept of feedback loops in context of traffic congestion.

The decision-making dashboard is designed as a primary tool for interaction with the model, the users are placed into the role of policymakers in urban planning and traffic congestion for the city of Bergen. The decision to present choices in four-year increments mirrors the political cycle, enhancing the simulation's authenticity and real-world connection. This aspect of the ILE design is a response to research that underscores the value of authentic learning experiences in promoting deep understanding and sustained engagement (Keith, Naumov & Sterman, 2017).

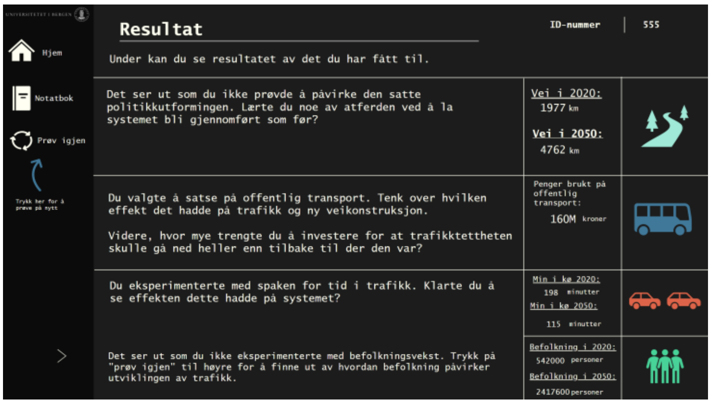
The dashboard interface is divided into two sections: the input interface and the output display. The input display has three parameters and two switches that the participant can operate to explore the system and create strategies (ILE Slide 7). In addition to the in-system variables, there are two buttons that manipulates the time of the model. One advances time by 4 years at a time, and the other restarts the model which reinitializes the model time to 2020 (20 years after the start of the model). This design choice is influenced by the understanding that clear visual representation of system components and relationships plays a crucial role in shaping the overall UX, enabling users to quickly grasp the system's layout and functionality (Card, Mackinlay, & Schneiderman, 1999).



Velg hvor mye du skal satse i den nye kampanjen om offentlig transport:

ILE Slide 7 – The interactive dashboard in which the participants are to use

After using the dashboard, the participants can either try again or continue to check the total results. This was incorporated after the interactive elements to consolidate learning and connect the participants' experiences with broader concepts. The results slide dynamic, based on the choices made by the participant (ILE Slide 8).



Under kan du se resultatet av det du har fått til.

Det ser ut som du ikke prøvde å påvirke den satte politikkutformingen. Lærte du noe av atferden ved å la systemet bli gjennomført som før?

Vei i 2020: 1977 km
Vei i 2050: 4762 km

Du valgte å satse på offentlig transport. Tenk over hvilken effekt det hadde på trafikk og ny veikonstruksjon.

Videre, hvor mye trengte du å investere for at trafikktettheten skulle gå ned heller enn tilbake til der den var?

Penger brukt på offentlig transport: 160M kroner

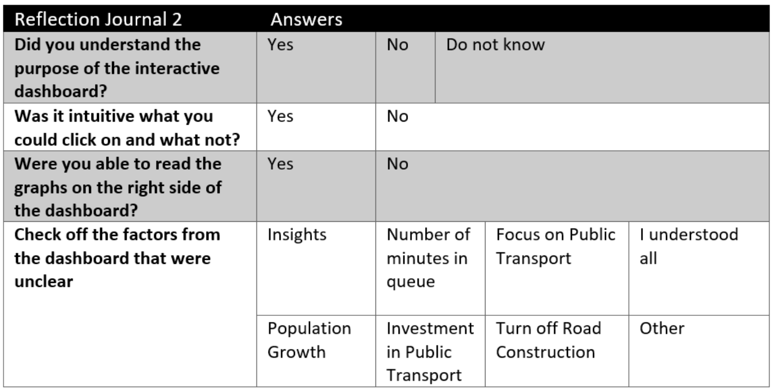
Du eksperimenterte med spaken for tid i trafikk. Klarte du å se effekten dette hadde på systemet?

Min i kø 2020: 198 minutter
Min i kø 2050: 115 minutter

Det ser ut som du ikke eksperimenterte med befolkningsvekst. Trykk på "prøv igjen" til høyre for å finne ut av hvordan befolkning påvirker utviklingen av trafikk.

Befolkning i 2020: 542000 personer
Befolkning i 2050: 2417600 personer

ILE Slide 8 – Dynamic Results Section



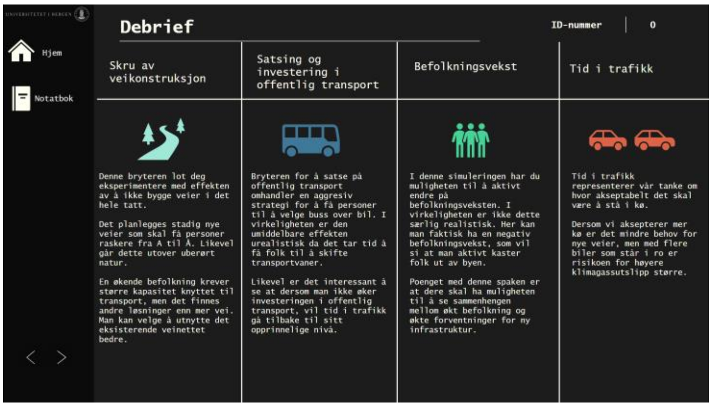
Reflection Journal 2	Answers			
Did you understand the purpose of the interactive dashboard?	Yes	No	Do not know	
Was it intuitive what you could click on and what not?	Yes	No		
Were you able to read the graphs on the right side of the dashboard?	Yes	No		
Check off the factors from the dashboard that were unclear	Insights	Number of minutes in queue	Focus on Public Transport	I understood all
	Population Growth	Investment in Public Transport	Turn off Road Construction	Other

Table 2 – Reflection Journal 2

After checking the results, the participant can either try the dashboard again, or continue to the second reflection journal. This journal aims to get information regarding the usability of the dashboard and whether the participants understood the tasks they were given (Table 2).

Finally, there is a debrief and conclusion. The first debrief page explains various factors affecting the system (ILE Slide 9). This choice was influenced by the belief that debriefing is a crucial part of experiential learning, reinforcing learning outcomes and fostering a deeper understanding of complex systems (Davidsen & Spector, 2015). The second debrief-page reintroduced the concept of feedback loops using the simulation they controlled in the dashboard as the context. At last, the participants are met with the conclusion which takes them out of the role as decision-makers, and they are invited to the last test, the post-test.

One can explore and examine the Interactive Learning Environment (ILE) by following this link (Ognøy, 2023). For any future examinations, I ask that ID 136 is used to bypass the home screen.



Debrief

Skru av veikonstruksjon	Satsing og investering i offentlig transport	Befolkningsvekst	Tid i trafikk
Denne bryteren lot deg eksperimentere med effekten av å ikke bygge veier i det hele tatt. Det planlegges stadig nye veier som skal få personer raskere fra A til Å. Likevel går dette utover uberørt natur. En økende befolkning krever større kapasitet knyttet til transport, men det finnes andre løsninger enn mer vei. Man kan velge å utnytte det eksisterende veinettet bedre.	Bryteren for å satse på offentlig transport omhandler en aggresiv strategi for å få personer til å velge buss over bil. I virkeligheten er den umiddelbare effekten urealistisk da det tar tid å få folk til å skifte transportvaner. Likevel er det interessant å se at dersom man ikke øker investeringen i offentlig transport, vil tid i trafikk gå tilbake til sitt opprinnelige nivå.	I denne simuleringen har du muligheten til å aktivt endre på befolkningsveksten. I virkeligheten er ikke dette særlig realistisk. Her kan man faktisk ha en negativ befolkningsvekst, som vil si at man aktivt kaster folk ut av byen. Poenget med denne spaken er at dere skal ha muligheten til å se sammenhengen mellom økt befolkning og økte forventninger for ny infrastruktur.	Tid i trafikk representerer vår tanke om hvor akseptabelt det skal være å stå i kø. Dersom vi aksepterer mer kø er det mindre behov for nye veier, men med flere biler som står i ro er risikoen for høyere klimagassutslipp større.

ILE Slide 9 – Debrief Explaining the Factors the Participants could Influence

Debrief: Hvor er ringvirkningene?

I simulatoren fikk dere muligheten til å påvirke forskjellige faktorer som påvirker styrken til de dynamiske ringvirkningene. Desto større befolkning, desto viktigere vil god og planlagt politikk være, og ved å være obs på dynamiske ringvirkninger som forårsaker mer veibygging, kan man forsøke å motvirke denne effekten.

For å motvirke økt trafikkbelastning må man tenke annerledes. Som vi allerede har sett vil flere og bredere veier kun være en kortvarig løsning. Man må derfor skape **motvirkende dynamiske ringvirkninger**. Offentlig transport kan være en sånn motvirkning. Dersom man investerer godt i offentlig transport og gjør det både komfortabelt og praktisk, vil flere velge buss, som vil redusere bilbruk som vil kunne gjøre det lettere å satse mer på buss.

En utfordring med slike strategier er at det krever politikk som tillater en betydelig økning i investeringer i offentlig transport.

ILE Slide 10 – Debrief of Feedback Loops

Phase 3: Pilot Study Experimental Design and Implementation

The final phase of the study launched into a pilot exercise that was primarily aimed at gathering data for testing the guiding hypotheses. This phase stood out due to its thorough experimental design, which incorporated the development of pre-tests and post-tests, meticulously structured classroom sessions, and a conscientious focus on ethical considerations.

The intention was to assess the students' foundational understanding, their interaction with the Interactive Learning Environment (ILE), their apprehension of essential concepts like feedback loops and policy comprehension, and their proficiency in making decisions within a sustainability framework. Exhaustive accounts of the construction of the tests, the procedure of implementation, and the ethical aspects considered are scrupulously delineated in the upcoming sections.

Hypotheses:

The hypotheses that influenced data collection were anchored in the design philosophy behind the ILE. The ILE, being an evolution and enhancement of previous educational paradigms, suggested that students who used it would gain a deeper understanding of the concepts taught. The hypotheses were formally stated as:

> *H0: There will be no difference in the pre and post test scores of all students using the ILE at an alpha of 0.05.*
>
> *H1: There will be a difference in the pre and post test scores of all students after using the ILE at an alpha of 0.05.*

This hypothesis investigates RQ1, which seeks to measure if the ILE is broadly useful for improving understanding of feedback and systems thinking.

> *H0: There will be no difference in the pre and post test scores of all students who have identified the ILE as beneficial at an alpha of 0.05.*
>
> *H1: There will be a difference in the pre and post test scores of all students who have identified the ILE as beneficial at an alpha of 0.05.*

This hypothesis investigates RQ1, seeking to understand if improvement in understanding, i.e. an improvement in performance is related to the students appreciation of the ILE.

While the primary objective was indeed the collection of data for the thesis, the goal sought to go beyond the mere aggregation of data. The aspiration was to utilize the gathered data to verify the outlined hypotheses and generate invaluable insights into the effect of the simulation design on students' understanding and learning.

Scoring Procedure:

Scoring procedures form an integral component of both qualitative and quantitative research methodologies, serving as a systematic and objective mechanism for interpreting and analyzing data (Stave, Beck & Galvan, 2014). In the present study, scoring methodologies are employed to transform raw data gleaned from the pre-test into a format that is more accessible for comprehensive analysis (Kim & Andersen, 2012).

By ensuring an accurate and consistent representation of participant's perspectives, comprehension, and engagement, the scoring procedure significantly enhances the objectivity of data interpretation and analysis (Stave, Galvan & Becker, 2014). The conversion of participant responses into numerical data permits comparative analysis of pre-test and post-test results, a crucial aspect in assessing the effectiveness of the educational intervention.

Due to the variance in total scores between the pre-test and the post-test, scaling of scores will be executed. The scaling procedure involves dividing the participant's score by the total potential score, ensuring fair and proportionate representation of participant performance across different testing phases (Twentyman et al., 2006).

Development of Pre-Test

Crafting an effective pre- and post-test for the study presented significant hurdles, particularly given the anticipated lack of participants' prior knowledge in system dynamics and systems thinking. The design of these tests, therefore, had to be especially careful. The pre-test aimed to subtly assess participants' understanding and interest in related subjects, while the post-test took a more direct approach to gauge the knowledge they had gained.

The pre-test was structured into two distinct sections, along with an additional section for unique participant identifiers. The first section intended to measure participants' interest in, and understanding of, complex subjects such as sustainability and global warming. These topics were chosen due to their intricate and interdependent systems, posing a suitable challenge for initial evaluation (Joshi et al., 2015). The analysis of responses would, therefore, allow us to establish a baseline of prior knowledge. The methods of deduction followed existing research, which demonstrates the validity of using such complex topics for initial baseline studies (Joshi et al., 2015).

Aiding the multiple-choice questions, incorporated reflection questions assess the capacity of participants for introspection and critical thought on these topics. The choice of using multiple-choice questions more over long-form was guided by research suggesting that this format is allows for easier and more reliable quantitative analysis (Joshi et al., 2015). The purpose was to combine responses, providing an indication of their pre-existing knowledge. Despite most questions being structured in a multiple-choice format, the pre-test also incorporated open-ended questions to provide a broader range of responses. Additionally, a singular question was specifically designed to yield a binary outcome – correct or incorrect – therefore augmenting the range of data collected (Table 3).

Response Type:	Scoring:
Self-Reporting of Interest and Understanding (Quantitative)	1 (Very little/No) - 5 (Very High)
Distinguishing Questions:	0 (Incorrect) – 5 (Correct)
Long-Form Responses (Qualitative)	1 (Superficial Understanding) - 5 (In-depth Understanding)

Table 3 - Example of the Scoring Procedure

To quantify this data, a Likert scale was used, allowing scoring of each participants response. The use of Likert scales is popular in social science research as it effectively quantifies qualitative attributes, transforming individual subjectivity into objective, quantifiable data (Joshi et al., 2015). However, there is a debate surrounding the choice of the number of points on a Likert scale, as well as whether it should be treated as an ordinal or interval scale. These considerations were kept in mind while using a Likert scale in the pre-test (Table 4). As the pre-test is somewhat shorter than the post-test, the scores will be scaled based on total potential score. This makes it possible to compare results more easily (Twentyman et al., 2016).

To ensure the validity and reliability of the pre- and post-tests, the design and coding approach adopted in this study were deeply rooted in the existing literature. This rigorous approach helped ensure that the methods were in line with established best practices (Joshi et al., 2015).

Multiple Choice Questions:	**Long-Form Questions:**
To what extent would you say you are interested in issues related to climate and global warming?	Sustainability is about finding ways to meet our current needs without compromising the ability of future generations to meet their needs. What do you think is the most significant environmental issue Bergen faces today? Why is it important?
To what extent do you feel that you understand issues related to climate and global warming?	
To what extent would you say you are interested in sustainability?	Our society faces many environmental issues, such as climate change, pollution, deforestation, and biodiversity loss.
To what extent would you say you understand the concept of sustainability and green transition?	Can you think of a system that is important for sustainability, such as a natural ecosystem, an energy system, or a transportation system?
To what extent would you say you understand how to arrive at sustainable decisions?	Solving environmental problems is challenging and can be seen as a complex task.
Which of the following definitions best describes sustainability?	What do you think could be the biggest obstacle to addressing environmental issues today?

Table 4 - Pre-test questions

Development of Post-Test

The Post-Test (Tables 5, 6, 7, 8, 9) is a combination of various sections, each designed to target different aspects of understanding and application. These sections include user experience, understanding of feedback loops, policy understanding, feedback loop identification, decision-making in the context of sustainability, and a concluding section. These sections were necessary to collect the data necessary to answer each of my research questions #1-#3.

User Experience

In the User Experience section (Table 4), participants respond to inquiries pertaining to their experience using the Interactive Learning Environment (ILE). Feedback regarding the ILE is deemed to be of significant value for the enhancement of the learning tool. Ideally, participants are prompted to provide this feedback immediately upon completion of the ILE exercise. This section integrates both reflective questions and multiple-choice queries.

Open-form questions are incorporated with the aim of eliciting insightful responses that could potentially shed light on the strengths and areas of improvement of the ILE. On the other hand, the multiple-choice questions provide a more quantifiable measure of the participants' experiences, ranging from 'to a small extent (0)' to 'to a large extent (5)'. The latter question format is considered more reliable, particularly if participants are reticent to delve deeply into their responses to the reflective questions (Vinten, 1995).

User Experience: Reflection Questions	
Were there any features or aspects of the learning tool that you found useful for your own understanding and learning of the topic? Please mention everything you can think of.	
Were there any features or aspects of the learning tool that you did not like? Please mention everything you can think of.	
User Experience: Multiple Choice	Range of answers: (for all questions)
To what extent would you say that the ability to develop your own strategies in the learning tool influenced your understanding of traffic problems?	To a small extent
To what extent would you say that the ability to develop your own strategies in the learning tool influenced your understanding of sustainability issues?	To a slightly greater extent
To what extent would you say that the ability to develop your own strategies in the learning tool influenced your understanding of dynamic feedback loops?	Neither/nor

To what extent did you enjoy experimenting with strategies in the dashboard?	To a moderate extent
To what extent did you feel that you understood the behavior in the graphs on the right side of the dashboard? How many times did you replay the simulator to try new strategies?	To a large extent
To what extent did you understand the content on the results page?	

Table 5 – Post-Test: User Experience Section

Understanding of feedback loops

The section of the post-test dedicated to feedback loop comprehension (Table 6) is designed to evaluate the participant's newly acquired understanding of this concept. To facilitate this, the participants are initially presented with a multiple-choice question that prompts them to select the correct definition of a feedback loop. The careful construction of the alternatives is crucial to ensure the question poses a meaningful challenge, thereby facilitating the differentiation of participants who have grasped the concept. The wrong answers can potentially make it possible to identify participants that have not understood the goal of understanding feedback loops (Abdelgawad et al., 2017).

Understanding of Feedback Loops: Multiple Choice	
Which of these four definitions best describes what a dynamic feedback loop is?	A process where the system produces an outcome or reaction that is irrelevant to the starting point.
	A process where the system produces an outcome or reaction that is randomly generated.
	A process where the system produces an outcome or reaction that is fed back into the system to generate new reactions. (Correct answer)
	A process where the system produces an outcome or reaction that demonstrates a correlation between different factors.
Understanding Feedback Loops: Reflection question	
Could you try to explain what a dynamic feedback loop is in your own words? Feel free to provide an example.	

Table 6 – Post-Test: Understanding of Feedback Loops

Following, participants are offered an opportunity to try to explain their understanding of a feedback loop in their own words, and they are encouraged to provide examples to illustrate their explanations. Responses to this open-ended question have the potential to yield significant insights into the depth of the participant's understanding of the concept (Vinten, 1995).

Understanding Policies

The section of the post-test focusing on understanding policies (Table 7) is designed to evaluate participants'' comprehension of various policy strategies and their potential effects on emissions, specifically within the context of the Bergen region.

The multiple-choice question offers several policy options and asks participants to select those they believe would be most effective in reducing emissions. This provides insights into the participants'' understanding of the relative benefits and drawbacks of different policy strategies, as well as how these strategies might interact within a complex system like a city's transportation network. The variety of policy strategies presented here - ranging from infrastructure changes to economic incentives - might also indicate how the interactive learning environment (ILE) has influenced participants' views on the multifaceted nature of policymaking.

Question	Policy	Score
Which of these strategies do you believe are best for reducing emissions in the Bergen region? (You can select multiple)	Building more roads to accommodate more cars	1
	Canceling all road construction projects	4
	Heavy investment in public transportation	5
	Accepting more time in rush hour traffic	3
	Reducing prices of electric cars (subsidies)	2
Understanding Policies: Reflection Question		
Can you think of any other policy measures that can be used to reduce emissions in Bergen and the surrounding area? All contributions are valuable.		

Table 7 – Post-Test: Understanding Policies

The open-ended question invites participants to propose additional policy measures to reduce emissions in Bergen and the surrounding area. The diversity and creativity of these responses can reveal the extent to which the ILE has stimulated participants' critical thinking and problem-solving skills in relation to policymaking for sustainability. The scoring for each response (as detailed in Table 7) derives from the model and ILE outcomes, as well as researcher conjectures. For instance, a participant opting for "Building more roads to accommodate more cars" or "Reducing prices of electric cars" would receive a lower score compared to one choosing "Heavy investment in public transportation". These scores serve as a benchmark for the actual grading, with the maximum potential points for a question capped at 5.

Identifying Feedback Loops

A further approach to discerning the participants' grasp of the feedback loop concept involves evaluating their ability to identify descriptions of feedback loops within different systems. In this section of the post-test (Table 8), participants are presented with four distinct explanations of feedback loops in three separate contexts.

Identifying Dynamic Feedback Loops: Multiple Choice Questions	
Which of the following represents a dynamic feedback loop in a system?	The number of people buying tickets to a concert has an impact on how many hear about the concert and therefore choose to buy a ticket.
	The number of people buying tickets to a concert increases the earnings for the band that will perform.
	The number of people in the band has an effect on the number of people attending the concert.
	The number of people buying tickets has an effect on the number of available tickets.
Which of the following represents a dynamic feedback loop in a system?	The population size has an effect on the size of a country, which in turn affects the population size.
	The population size has an effect on the number of births, which in turn affects the population size.
	The population size has an effect on the number of cities in a country, which in turn affects the population size.
	The population size has an effect on the number of cars in a country, which has an effect on greenhouse gas emissions.
Which of the following represents a dynamic feedback loop in a system?	A farmer cultivates crops and sells them at a local market, which provides income for the farmer to buy supplies for the next season.
	A factory produces small parts and sells them to customers who use them to complete various tasks.
	A group of friends goes on a mountain hike, enjoys the view, and gets exercise.
	A teacher delivers a lecture to a class of students who take notes and ask questions to better understand.

Table 8 – Post-Test: Identifying Feedback Loops

The idea is that if the participants can correctly identify the accurate system component, this suggests a more comprehensive understanding of the nature of a feedback loop and how to identify them (Abdelgawad et al., 2017).

Decision Making and Sustainability

The section of the post-test (Table 9) focusing on decision-making and sustainability seeks to assess the participants' understanding and attitudes regarding the long-term effects of sustainable versus unsustainable decisions, the perceived value of the learning tool in enhancing this understanding, and their subsequent interest in sustainability and green decision-making.

The first question invites participants to contemplate the trade-offs between infrastructural development and environmental conservation. Their responses can provide insights into how they prioritize and balance these considerations, potentially revealing the influence of the interactive learning environment (ILE) on their perspectives.

The second question asks participants to reflect on the application of the ILE's features, such as the ability to generate 'what if' scenarios, in facilitating sustainable decision-making. Responses can illuminate how participants perceive the practicality and usefulness of the tool in real-world contexts, thus providing a measure of its effectiveness in promoting systems thinking.

Decision-Making and Sustainability: Reflection Questions	
One of the graphs you could observe was how road construction has a direct impact on the destruction of untouched nature. **To what extent do you believe that preserving untouched nature is important despite potentially hindering future road projects?**	
In the learning tool, you have been given the opportunity to experiment with different strategies and create multiple "what if" scenarios. **Do you believe this can be used to make good and sustainable decisions? If so, how?**	
Decision-Making and Sustainability: Multiple Choice Questions:	
To what extent did the learning tool help you understand the long-term effects of sustainable and unsustainable decisions?	To a small extent
	To a slightly greater extent
	Neither/nor
	To a moderate extent
	To a large extent
To what extent do you feel that you have increased your understanding of the importance of sustainable strategies by using the learning tool?	To a small extent
	To a slightly greater extent
	Neither/nor
	To a moderate extent
	To a large extent
To what extent did your interest in sustainability and green decision-making increase after using the learning tool?	To a small extent
	To a slightly greater extent
	Neither/nor
	To a moderate extent
	To a large extent

Table 9 – Post-Test: Decision Making and Sustainability

Lastly, the multiple-choice questions seek to gauge the extent to which participants believe the ILE has helped them understand the long-term effects of sustainability-related decisions, increased their comprehension of the importance of sustainable strategies, and heightened their interest in green decision-making. This quantitative data can provide a more precise, measurable assessment of the tool's impact on participants' understanding and interest in sustainability (Stave et al., 2015). Wrong or unengaging questions on the other hand could suggest that the ILE has faults.

Classroom Session

The pilot study was carried out over two sessions. The first session involved an introduction to the study, where students were provided with an explanation of the procedure and their rights as participants were given. Prior to this session, the students' teacher had already disseminated information about the study via Fremtenkt, my partner organization. Upon concluding the introductory session, students were asked to complete the pre-test. A unique identifier was assigned to each student for use in all future data collection points, including the pre-test, the ILE, ILE-journals, and the post-test. The students kept the unique identifier with them, while the teacher maintained a list of these identifiers as a safety measure against potential loss or forgetfulness. It's important to note that I did not participate in the process of assigning the unique identifiers and hence remained unaware of the identifiers' respective owners.

The second session was conducted two days following the initial one. In this session, students were prepared to engage with the ILE. They were granted a time of one and a half hours to navigate the ILE, respond to the ILE-journals, and complete the post-test. As a token of appreciation for their participation, students were provided with pastries at the end of the session. The teacher facilitated the unique identifiers for those who had difficulty remembering them. Again, my involvement did not extend to facilitating the unique identifiers.

I had the opportunity to personally observe the ILE testing session. During this observation, I noted that students primarily encountered challenges concerning user experience, largely originating from compatibility issues or difficulties with their chosen web browsers. Addressing these challenges occasionally proved to be arduous. Based on this experience, I recommend instituting a "preliminary ILE" phase in future ILE testing sessions, aimed at identifying and rectifying any technical difficulties prior to initiating the primary evaluation. This approach might enhance the efficiency of the testing experience.

The teacher's presence during the testing session was instrumental in sustaining student focus and engagement. Their enthusiasm and collaboration with me in promoting the experiment might have amplified trust and acceptance among the students. However, it is essential to acknowledge the potential influence of a teacher's presence on the students' responses during the testing session. Future research could delve into the implications of the teacher's involvement in ILE evaluations, thereby shedding light on their impact on experimental outcomes.

Ethical Considerations

Given the nature of the study, particularly with its focus on high school students, significant ethical considerations were necessary to ensure the respect, privacy, and welfare of the participants (Denscombe, 2012). The following is a list of considerations taken.

1. **Informed Consent:** The students were given comprehensive information about the study's purpose, the procedures they would undergo, and what their participation would entail. This included details on the time commitments, the types of activities they would be asked to engage in, and the potential benefits of the study. The students were also informed that they had the right to withdraw from the study at any time without any negative consequences. Consent forms were distributed and collected, with each student and their guardian signing to indicate they understood the study and agreed to participate.

2. **Anonymity and Confidentiality:** To maintain the participants' anonymity, each student was assigned a unique identifier, which was used in all data collection activities. This ensured that the data collected could not be directly linked back to any individual participant. The list linking the students' names to their unique identifiers was kept strictly confidential by the teacher and was not accessible to the researcher.

3. **Protection of Data:** All data collected during the study was stored securely to maintain privacy and confidentiality. Electronic data was kept on password-protected computers and servers, while physical data was kept in a secure location. Access to the data was limited to the research team, and all data will be destroyed once it is no longer needed for research purposes.

4. **Non-harmful Procedures:** The study involved non-invasive and non-harmful procedures, such as the completion of surveys and participation in the Interactive Learning Environment. The students were not subjected to any physical or psychological harm as a part of their participation in the study.
5. **Debriefing:** At the conclusion of the study, the students were debriefed and given an opportunity to ask any questions they might have about the study. They were also thanked for their participation and provided with information on how their contributions would help in understanding the effectiveness of the ILE.
6. **Ethical Approval:** Before the commencement of the study, ethical approval was obtained from UiB.Rette which ensured that the study was conducted in accordance with ethical guidelines and regulations.

In all these ways, the study was conducted with the utmost respect for the dignity, privacy, and welfare of the participants, in line with ethical guidelines for research involving human subjects.

Results:

This section presents the findings and analyses from the data collected during the study, which is primarily focused on the impact of the Interactive Learning Environment (ILE) on the students' learning outcomes. The structure of this section is divided into four main subsections: Results of Pre-test, Results of Post-test, Comparison of Pre-test and Post-test, and Evaluation of the ILE Design.

Pre-Test and Post-Test Data

The study involved two tests, a pre-test conducted on the first day and a post-test conducted on the second day. The pre-test followed an initial explanation of the experiment and was completed by 14 participants. On the second day, 9 of the original participants completed the ILE testing session and the post-test. Notably, one participant (487) completed the post-test but did not participate in the pre-test.

In the pre-test, scaled scores, which allow for easier comparison across different tests or test versions, showed a similar pattern of variation, ranging from 0.36 to 0.80, with an average of 0.53 (Table 10).

A combined table showing both pre-test and post-test data are presented below showing both total raw score and the total scaled score which is what will be used for the t-paired test.

Unique ID	Pre-Test Total Score	Post-Test Total Score:	Pre-Test Scaled Score	Post-Test Scaled Score:
410	17	32	0,38	0,53
880	28	35	0,62	0,58
681	23	36	0,51	0,60
562	33	33	0,73	0,55
433	16	34	0,36	0,57
487	-	50	-	0,83
904	36	43	0,80	0,72
345	26	35	0,58	0,58
420	16	27	0,36	0,45
725	33	26	0,73	0,43
177	17	-	0,38	-
555	28	-	0,68	-
633	17	-	0,38	-
371	17	-	0,38	-
231	29	-	0,64	-

Table 10 – Results from Pre-Test and Post-Test: Five participants did participate in the post-test even though they completed the pre-test, and one participant completed the post-test without first completing the pre-test.

The total scaled scores in the post-test range from a low of 0,43 to a high of 0,73, with several students achieving scores between 0,5 and 0,6. This suggests some variance in test scores between participants. The highest score was performed by participant 487 which did not complete the pre-test. It therefore cannot and will not be used in the statistical analysis, but might suggest a high level of understanding and participation.

In summary, the post-test data shows a range of scores, suggesting varying levels of understanding among the students after the ILE intervention. Further statistical analysis will allow us to understand more about the impact of the intervention and which factors may have influenced the students' post-test scores.

Comparison of Pre-Test and Post-Test Results

The comparison of pre-test and post-test outcomes is fundamental to this research, as it provides the basis for evaluating the efficiency of the ILE in increasing the students' understanding of feedback loops within the context of traffic congestion.

The mean scaled score demonstrated a minor decrement from 0.53 during the pre-test to 0.56 at the time of the post-test. A paired t-test was utilized to assess the statistical significance of this reduction. This method analyzes the mean disparity between linked observations (here, the pre-test and post-test scores) to determine if the difference holds any statistical relevance.

Despite the application of the ILE, the findings indicated that the null hypotheses for both Hypothesis 1 (H1) and Hypothesis 2 (H2) could not be negated given the p-value of 0.92. This value exceeds the alpha level of 0.05, affirming that the variation between the pre- and post-test scores of the students is not statistically noteworthy. This holds whether the students engaged with the ILE or specifically identified it as beneficial to their learning.

The statistical data resulting from the paired t-test is outlined in the table below:

Statistics	Value
Number of Participants in Both Tests	9
Mean Difference	-0.01
Standard Deviation Difference	0.16
T-Stat	-0.107
P-Value	0.92

Table 11 - Paired T-Test Results

With a p-value of 0.92, exceeding the accepted thresholds for significance (often 0.05 or 0.01), the null hypothesis asserting a zero mean difference remains unchallenged. Hence, there is little evidence to claim that the ILE intervention had a significant effect on the students' comprehension as per the test scores.

Furthermore, the standard deviation of the differences was 0.16, suggesting that there was a degree of variance in the alteration of students' scores from the pre-test to the post-test.

UX and Design Insights

This section presents the findings from the user experience portion of the post-test data collection. Feedback was analyzed from ten participants on various aspects of the learning tool. This includes the features they found useful, the elements they disliked, their enjoyment of experimenting with strategies in the dashboard, their understanding of the behavior of the graphs on the dashboard, the number of times they reran the simulator to try new strategies, and their comprehension of the content on the results page.

Table 12 summarizes the features that the participants found useful in the learning tool. As shown, the most frequently mentioned aspect was the ability to interact with the dashboard and the graphics it contained, which participants found facilitated their learning and understanding of the subject matter.

Participant ID	Features Found Useful
410	Self-response feature
880	Diagrams showing significant local polluters
681	Interactive learning method
562	Graphs showing CO2 pollution data
487	Entire tool
904	Graphs for learning
345	Interactivity and comprehensive initial instructions
725	Ability to experiment with traffic policy decisions

Table 12 - Features of the Learning Tool Found Useful

Table 13 summarizes the aspects of the learning tool that the participants disliked or found challenging. Several participants noted some confusion or difficulty with understanding certain features, while others commented on the excess of text or issues with the functionality of some graphs.

Participant ID	Disliked Features
880	Final part about going back in time and complexity of a specific diagram
681	Some graphs not functioning correctly
562	Lack of clarity on data sources
904	Excessive text; dashboard concept execution
345	Difficulty reading the graph; text placement; end-of-activity feedback

Table 13 – Disliked Features of the Learning Tool

On the aspects of experimenting with strategies in the dashboard, most participants reported enjoying this feature, with participant 420 being neutral. Most of the respondents also showed at least a moderate understanding of the behavior of the graphs on the dashboard, with only participant 345 reporting a lower level of understanding.

Regarding the number of times participants reran the simulator to try new strategies, the majority did so 2-3 times, suggesting a high level of engagement with the tool. Lastly, most participants reported a good understanding of the content on the results page, although a few noted less understanding.

The post-test survey sheds light on user understanding and usability of the interactive dashboard. Most participants demonstrated comprehension of the dashboard's goal and found its operations intuitive, with 8 out of 12 affirming their understanding of the goal and the same number finding it easy to distinguish between interactive and non-interactive elements. However, a few participants experienced difficulties or uncertainties, indicating the need for clearer explanations or more explicit guidance in future iterations of the tool (Table 14).

Questions	Yes	No	Maybe / I don't know	Not provided
Did you understand the goal of the interactive dashboard?	8	2	1	1
Was it intuitive what you could and could not click on?	8	3	-	1
Were you able to read the graphs on the right side of the dashboard?	9	2	-	1
Please tick the factors from the dashboard that were unclear	I understood the purpose of all (6)	Investment in public transport (2)	Number of minutes in traffic jam (1)	
	Turn off road building (3)	Population growth (1)	I don't know / Not provided (1)	

Table 14 – Counted Results of the Second Reflection Journal

Most participants were also able to comprehend the graphs on the dashboard, with 9 out of 12 confirming their readability. Yet, for a small group, enhancements in graph design might be beneficial for improved comprehension. Concerning the clarity of dashboard factors, while several participants comprehended all aspects, some indicated unclear factors such as

'Investment in public transport', 'Turn off road building', and 'Population growth', suggesting that more explicit definitions could aid understanding (Table 14).

These insights into the user experience provide valuable feedback for refining the learning tool's design and enhancing its effectiveness as an educational resource. Future improvements could address the areas of difficulty identified by participants, such as enhancing the clarity of the graphics and data sources, balancing the amount of text, and improving the dashboard's execution.

Specific Insights from the Pilot Study

In the post-test, the students were tested in questions related to identifying and understanding feedback loops (Table 6 and Table 8). When asked to pick out the correct definition on what a feedback loop is, 4 out 11 participants answered correctly.

Answer:	Count
A process where the system produces an outcome or reaction that is irrelevant to the starting point.	0
A process where the system produces an outcome or reaction that is randomly generated.	1
A process where the system produces an outcome or reaction that is fed back into the system to generate new reactions. (Correct answer)	6
A process where the system produces an outcome or reaction that demonstrates a correlation between different factors.	4

Table 15 – Result on question identifying the correct definition of a feedback loop

In the following question, the students are asked to explain what a feedback loop is themselves (Table 6). While three of the responses were empty, most participants attempted to answer the question. It appears that most participants, with participant 562 being the outlier, have grasped either the complete concept or parts of the feedback loops concept.

Number	Response
880	It's that a decision leads to new decisions. E.g., a new road leads to less congestion, which means that more people choose the car, and the queues become just like before.
681	I believe that dynamic feedback loop is various factors that can influence a result based on what the factors have previously collaborated/led to.
562	It's like a dynamic feedback loop if you understand.
904	Expanding roads initially leads to less congestion. New roads lead over time to more cars in traffic and new congestion. Therefore, road construction must be stopped at some point, and public transport must take over.

345	When something goes well, usually something else also goes well, and vice versa. If a football player scores a goal and becomes more confident, it will usually make him score many more goals in the future, than if he had not scored.
420	Car road is made, cars are driven on the road, and then again
725	Dynamic feedback loop is a form of social interaction that occurs when a person has a positive or negative impact on others, which in turn has an impact on the first person.
410	A dynamic feedback loop is when an outcome is affected by creating new influences in the process.

Table 16 – Response on open-form question on explaining feedback loops

The students were also asked to identify the correct observation of a feedback loop, choosing between some pre-set answers (Table 8). In Q1 and Q3, the majority of participants were correct, but in Q2 most participants chose a linear causality, not a circular one.

Which of the following represents a dynamic feedback loop in a system?			
Question 1:	Count		Count
The number of people buying tickets to a concert has an impact on how many hear about the concert and therefore choose to buy a ticket.	6	The number of people buying tickets to a concert increases the earnings for the band that will perform.	1
The number of people in the band has an effect on the number of people attending the concert.	2	The number of people buying tickets has an effect on the number of available tickets.	2
Question 2:			
The population size has an effect on the size of a country, which in turn affects the population size.	0	The population size has an effect on the number of births, which in turn affects the population size.	2
The population size has an effect on the number of cities in a country, which in turn affects the population size.	3	The population size has an effect on the number of cars in a country, which has an effect on greenhouse gas emissions.	6
Question 3:			
A farmer cultivates crops and sells them at a local market, which provides income for the farmer to buy supplies for the next season.	6	A factory produces small parts and sells them to customers who use them to complete various tasks.	3
A group of friends goes on a mountain hike, enjoys the view, and gets exercise.	0	A teacher delivers a lecture to a class of students who take notes and ask questions to better understand.	1

Table 17 – Multiple Choice on Feedback Loop Observations – green fields are the correct answers.

In the end of the post-test (question 22), the participants were asked whether they believe the ILE has contributed to increase their interest in sustainability and green decision-making (Figure 4). Most participants report that it did not have any effect on their interest (green), and only two participants were positive that it had contributed to their interest (red and purple).

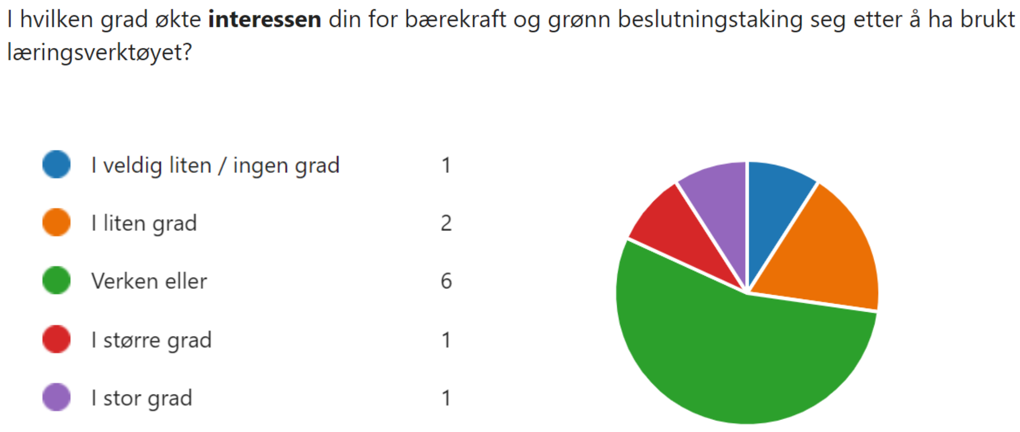


Figure 10 – Question regarding their interest in sustainability and green decision-making

Question 22 can be compared with the open-form and last question where the students are asked to conclude and report on any thoughts and ideas they had about the ILE and Pilot Study (Table 18). While only six participants responded, their comments can be a useful way of increasing the understanding of what needs to be improved.

ID	Responses:
410	I think this was superb.
880	One must try to make the changes one can, for example, take the bus if possible. Learn about the problems we face so that we can try to solve them in a better way, at least try to make an effort and participate.
681	Quite an acceptable way to learn.
487	I have no further comments.
904	I would generally say that a little fine-tuning is needed, but it's a good tool. The text between the tasks could be shortened, and the dashboard could be made around a slightly more interesting theme.
420	No.

Table 18 - Finally, do you have any last comments that you think are important to express in relation to the use of this learning tool?

It should be noted that four out of six comments are short and give little constructive to work with, but Participant 880 shows engagement by mentioning policies and concludes what they have learned, and Participant 904 comments that they like the tool, but suggests that some fine-tuning could be needed. It assumed that the participant is talking about technical and visual issues due to comments received in the classroom session. Participant 5 also suggests that the dashboard could be used for experimenting with a theme that is slightly more interesting than traffic congestion. Additionally, when asked how many times they tried the dashboard, most participants reported to have tried the dashboard more than once (Table 19).

Number of Reruns	**Participant Count**
Only once	1
2-3 times	6
4-6 times	2
6-8 times	0
More than 8 times	0
Don't remember	1

Table 19 – Results on question regarding how many times they tried the dashboard

Discussion:

This section will discuss how the collected data can be used to address the research questions presented in the introduction. First, I will discuss the findings for research question one (RQ1), which examines the influence of an Interactive Learning Environment (ILE) on high school students' understanding of systems thinking concepts related to traffic congestion. Next, I will delve into research question two (RQ2), which investigates whether a traffic congestion-themed ILE effectively introduces high school students to the concept of feedback loops. Finally, I will address research question three (RQ3), focusing on the challenges and limitations reported by the researcher regarding the implementation of ILEs in a high school classroom setting. The responses to RQ3 will be discussed in the context of the pilot study completion and the insights gained from studying human-computer interaction (HCI) and user experience (UX).

ILEs for Increasing Understanding of ST-concepts for Traffic Congestion

The first research question is not easily answered based on the results of the data collected. Even though the results were statistically insignificant, they show that some of the participants found the ILE to be both educating and engaging (Table 12, 14, 15). On the other hand, most participants reported to be indifferent to whether the ILE-experience did or did not increase their interest within the subject (Figure 10). This question, though not directly measuring RQ1, can still serve as an indicative measure. Alongside the non-statistical result, it suggests that the specific ILE has had limited impact on enhancing students' understanding of Systems Thinking within the context of traffic congestion.

There can be many reasons to explain why the ILE in little extent has influenced their understanding of ST concepts for traffic congestion. These include internal factors such the quality of the education content or ILE design, poorly formulated questionnaires that do not catch their thoughts and ideas or possibly choice of demographic for the chosen theme of the ILE. There is also a possibility of external factors influencing this such as their previous interest, knowledge and understanding of the theme, comfort level with the ILE, or something else entirely.

Understanding Feedback Loops: An Examination of ILE Effectiveness

The second research question (RQ2), can be more easily answered as this was directly evaluated in the post-test. It is presumed that if students can identify and explain feedback loops to a certain extent, they have achieved some level of understanding. However, this thesis does not delve into the depth of this understanding.

A close analysis of the collected data reveals an interesting trend; while most participants struggled with picking the correct pre-set definition of a feedback loop (Table 15), they were surprisingly good at describing the concept in their own words when given the freedom to do so (Table 16). This observation suggests some level of understanding among the participants, but the relatively small sample size cautions against making any definitive conclusions.

When analyzing the participants response to feedback loop observation questions (Table 16), some interesting observations were made. Most participants showed a good comprehension of feedback loops in their correct responses to Q1 and Q3 (Table 16). This outcome indicates a level of understanding, as most students correctly identified the circular cause-and-effect nature of feedback loops even when presented with linear concepts.

However, a noticeable change in responses was observed in Q2, where most students selected one of the linear answers. The reasons behind this are likely multifaceted. The wording or framing of the questions might have been confusing, leading to the students leaning towards linear responses. Alternatively, it could suggest that the concept of feedback loops may still be challenging for some students to fully grasp, especially when presented with complex or less straightforward scenarios.

In addressing RQ2, the findings from the post-test might indicate that the ILE effectively introduced the concept of feedback loops to the students. This assumption is supported by most participants demonstrating their ability to clearly describe feedback loops and correctly select between different observations. Although there were some exceptions, such as the pre-set question about feedback loop definitions and Q2 in the identification task, the data suggests a non-statistical indication that most participants achieved some level of comprehension of feedback loops.

Challenges and limitations of implementing ILEs in a high school classroom

This discussion is grounded in the results of the statistical analysis and the general experience of the researcher in performing this pilot study. Addressing the third research question, this study explores the challenges and limitations that must be considered before implementing an Interactive Learning Environment in a high school classroom. This aspect of the study is presented with some confidence as it extends from the researcher's experiential learning gained during the model's development and its implementation as an ILE in the pilot study.

One significant challenge faced during this implementation was reaching the intended demographic - high school students. This study was fortunate to partner with Fremtenkt, an organization already engaged in sustainability workshops at high schools (“Fremtenkt,” 2023). However, the access was limited to a single class, restricting the ability to test the ILE properly. Greater access to more classes would enhance the robustness of the study by providing higher quality and more diverse data. An alternative approach could involve directly contacting schools, although this method might present its own set of challenges.

Another challenge met was related to the theme of the ILE which centered on traffic congestion (Table 15). The rationale behind choosing this theme was to provide a local context to the study, given the current relevance of traffic-related issues in Bergen (Eriksen, 2023).

Ensuring that the theme resonates with the intended demographic remains a critical factor for engagement and effectiveness of the ILE. To address this challenge in future iterations, it may be advantageous to either consult with the class teacher or conduct preliminary research to understand the interests and concerns of the target student group. This way, the theme of the ILE could be tailored to enhance its relevance and appeal to the students, thereby potentially fostering a higher level of engagement and interest.

Complications also occurred during the pilot study itself. Conducted over two full class sessions (totaling 3 hours), the study was structured with the pre-test administered on the first day and the testing session and post-test on the second day. This format created difficulties in tracking the progress of individual participants, particularly given the varying attendance between the two days. This unfortunate circumstance hindered an efficient utilization and analysis of the collected data. In future projects it would therefore be highly recommended that pre-test, ILE-testing, and post-test is performed in the same day or in a more organized matter than what was the case for this study.

Technical issues presented another challenge during the class sessions. On the first day, students encountered difficulties accessing the QR-code for the pre-test, leading to disruption and a need for teacher intervention to regain focus. On the second day, students experienced technical problems with the ILE itself, hosted on the servers of the ISEE exchange. Reports included loading difficulties and blank pages within the ILE interface.

These technical issues warrant careful consideration, as such disruptions can lead to confusion and loss of focus among participants. The study underscores the importance of ensuring a smooth and efficient technical operation of the ILEs to maintain student engagement and facilitate learning. These insights into potential challenges and limitations of implementing ILEs in a classroom setting can inform future implementations and contribute to the continual development and refinement of such educational tools.

For future research, a list of considerations when implementing an ILE in a high school classroom is presented. Some of these reflections are shared with (Zimmermann et al., 2021).

1. **Find the Right Partners:** Look for partnerships with organizations that are already involved in schools. This can help you reach more students and get more diverse data.
2. **Pick Topics that Interest Students:** Choose a theme for the ILE that matches what the participants are interested in. This could involve talking to the teacher or doing some research about what the demographic like.
3. **Keep Data Collection Consistent:** Try to do all testing (pre-test, ILE-testing, and post-test) on the same day or in a more organized way. This helps keep the data clear and easy to analyze.
4. **Fix Technical Problems Quickly:** Make sure to handle any technical issues that could interrupt the students' use of the ILE. This includes things like making sure QR

codes work properly and that the ILE itself runs smoothly. Regular checks and updates can help prevent technical problems.

5. **Make the ILE Easy to Use:** Design the ILE to be easy for students to navigate and interact with. Test it with peers, friends, and people similar to the demographic. The easier it is for the participant to use, the more effectively they can learn from it.
6. **Be Ready for Changes in Attendance:** Plan the pilot-session with the understanding that not all participants might be present for every session, and to plan for unplanned events.
7. **Keep Improving the ILE:** Use feedback and what you observe to keep making the ILE better. It should meet the participants needs and help them reach the goals of the class.

The Role of UX and HCI in Enhancing the Experience of ILEs

Based on the feedback received during the development phase, the post-test, reflection-journals, and pilot study, several insightful considerations can be derived concerning the user experience (UX) and human-computer interaction (HCI) aspects of interactive learning environment (ILE) development.

Analyzing Table 12, it becomes evident that interactive features and visual aids, such as diagrams and graphs, were highly valued by the participants for enhancing their learning experience. Participant 345's comment on appreciating the comprehensive initial instructions points to the importance of clear guidance, setting the tone for a successful engagement with the ILE.

Nevertheless, as highlighted in Table 13, there were some areas that the participants found challenging. These included issues related to the functionality of some graphs, the excess of text, and lack of clarity on data sources. The challenge with text placement and end-of-activity feedback, as reported by Participant 345, underscores the necessity of a well-structured interface that balances readability, accessibility, and user-friendliness. Moreover, Participant 880's difficulty with a complex diagram and a conceptually demanding final part, emphasizes the need for simplicity and incremental complexity in the learning process.

Examining the aspect of experimentation with strategies, it is positive to note that the participants reported a high level of engagement with the tool. This is evident in the fact that most participants reran the dashboard 2-3 times to try new strategies (Table 19). Their understanding of the content on the results page was mostly good, but some reported less understanding, suggesting areas for improvement.

Responses (Table 14) reveal areas requiring explicit guidance or clearer explanations in the tool's future iterations. Eight participants understood the dashboard's goal and could easily distinguish between interactive and non-interactive elements. However, some experienced difficulties, indicating the need for further clarification. Specifically, certain factors like 'Investment in public transport', 'Turn off road building', and 'Population growth' were found unclear by some participants, suggesting that their definitions need to be made more explicit.

Feedback for the Interactive Learning Environment was asked from various sources, including peers, beta-testers, and participants in the pilot study. This input provides valuable insight into the perceived efficacy and usability of the ILE.

A common sentiment expressed across many of the responses was an appreciation for the modern aesthetics of the ILE. Respondents found the design to be visually appealing, a factor which they indicated contributed to sustained engagement with the tool.

Another central point of the feedback was the design of the dashboard. While some respondents suggested that its complexity could potentially pose difficulties for high school students, this concern was largely reduced after the pilot study. Despite initial worries, a significant portion of the participants reported finding the dashboard both understandable and user-friendly, as shown by the data presented in Table 14.

This qualitative feedback underscores the importance of both aesthetics and functional design in maintaining a user-friendly learning environment. It also suggests that, despite initial concerns, the dashboard's complexity was not prohibitive for most users, and could indicate a successful balance between functionality and accessibility.

Based on discussion on HCI, UX and design of the ILE, a list will be presented which can be useful for future iterations within the same or similar fields:

1. **Iterative User Feedback:** Regularly collect and integrate feedback from users to continuously improve the design and functionality of the ILE. This allows the development team to respond to specific user needs and preferences.
2. **Simplicity and Clarity:** Ensure that the interface is simple and easy to understand. Avoid excessive complexity in diagrams and data presentations to make the tool more accessible to users with varying levels of prior knowledge.

3. **Interactive Design:** Continue to incorporate interactive features and visual aids, as these were found to be highly appreciated by users for enhancing the learning experience.
4. **Clear Instructions:** Maintain comprehensive initial instructions and guidance throughout the ILE to ensure users understand how to engage with the tool effectively.
5. **Functional and Aesthetic Balance:** Strike a balance between aesthetics and functionality. A visually appealing design encourages sustained user engagement, but this should not compromise the usability and functionality of the tool.
6. **Text Balance:** Consider the amount and placement of text. While providing enough detail is important, excessive text can overwhelm users and detract from the interactive experience.

Limitations and Improvements

Beyond the already discussed limitations and possible enhancements associated with the use of Interactive Learning Environments (ILEs) in high school settings, this section offers further insights. Based on the collected data, it's clear that students generally had a positive response towards the ILE. However, it's not certain whether they completely understood the concept of feedback loops. Furthermore, it remains difficult to determine if this application to the simulation-based method to teach the theme of traffic congestion, specifically in a localized context such as Bergen, offers advantages over more conventional pedagogical approaches.

A significant limitation and potential area for improvement of this research concerns the design of the pre-test and post-test. Given the introduction of entirely new concepts, assessing any increase in understanding was a difficult task. Future versions of this study or similar research should put significant effort into developing the pre-test and post-test to allow for a more accurate measurement of students' understanding of Systems Thinking.

The feedback received from students suggests that both the ILE and the questionnaires were user-friendly. However, upon reviewing the collected data, I realized there were other questions that would have been useful to ask. These could include inquiries about students' opinions on the design of the ILE and whether they enjoyed using it. Additionally, choosing a theme that is more relevant or interesting to the students could have been beneficial.

Further Research:

As previously emphasized, the aspect of time management is critical and warrants careful consideration in future investigations. Specifically, this refers to the time investment required for developing a computational model, the ILE, and the instrumentation for the pre- and post-tests. Future researchers should account for the considerable amount of time and effort required to construct these components adequately.

Further, the design of the pre- and post-test questionnaires and the following coding and interpretation of results demands considerable forethought and strategic planning. In this study, it was challenging to code the data effectively, particularly as there was no predetermined plan for how to analyze and interpret the collected data. This unplanned approach resulted in obstacles that, in retrospect, could have been avoided. Future research should, therefore, underscore the importance of devising a clear plan for data coding and analysis prior to conducting data collection, to facilitate a smoother and more efficient interpretation of results.

A further point of consideration is the size of the participant pool. In this study, it was observed that the initial number of planned participants could diminish over the course of the research, due to unforeseen circumstances. Therefore, it is strongly recommended that future studies consider a larger sample size of at least 30 participants, or more, to account for potential decline and unforeseen circumstances that may result in fewer participants than originally anticipated.

Conclusion:

This study presents an exploration of the use of Interactive Learning Environments (ILEs) for attempt to develop comprehension of Systems Thinking, specifically in the context of traffic congestion, within a high school environment. The research presents some insights and further emphasizes both the potential and challenges of such an approach.

Building upon the established theories and methodologies of systems thinking and system dynamics discussed in the literature review, the research sets out to research the role of ILEs in facilitating an in-depth understanding of complex systems. The systems thinking and system dynamics perspective, with its inherent focus on how feedback loops and delays affect systems.

This study has delved into the educational potential of ILEs in a high school setting. While the results did not categorically reveal an enhancement in the understanding of Systems Thinking within the context of traffic congestion, they did possibly suggest that an ILE can serve as both an instructive and engaging tool for students. The effectiveness of this tool, however, could be based upon addressing certain influential factors such as the quality of educational content, ILE design, questionnaire design, the choice of student demographic, and their prior knowledge and interest in the subject matter.

One of the key insights of the study is the reaffirmation of the critical role of User Experience (UX) and Human-Computer Interaction (HCI) considerations in the development and successful implementation of an ILE. Based on the feedback from students, factors such as aesthetics, functional design, clear instructions, simplicity, and interactivity were identified as crucial to improving the user experience and facilitating learning.

The study also highlighted a range of challenges associated with the deployment of ILEs in high school classrooms. These included reaching the intended demographic, selecting an engaging and relevant theme, ensuring consistency in data collection, promptly addressing technical issues, designing the ILE for ease of use, and continually improving the ILE based on feedback and observed needs.

The research faced a substantial level of limitations, particularly related to the design of the pre-test and post-test and participant pool. Despite these challenges, the study opens avenues for future research. Recommendations for subsequent investigations include careful time management, strategic design of questionnaires and data analysis plans, and a consideration of larger sample sizes to offset potential dropouts.

The research further suggests exploring other themes that may resonate more with the students, thereby potentially enhancing their engagement and the effectiveness of the ILE. For instance, studies within System Dynamics, as reviewed in our literature review, have demonstrated its capabilities in analyzing and understanding complex systems across a range of fields, including health systems enhancement, environmental problem comprehension, and supporting decision-making processes. These alternative themes could potentially be leveraged to spark interest and enhance understanding of Systems Thinking among students.

The research offers a nuanced understanding of the potential and challenges associated with the implementation of ILEs in high school settings. It adds to the growing body of literature advocating the value System Dynamics and simulation-based learning such as ILEs as methods for understanding and addressing complex problems, both within educational contexts and more.

This study serves as a potential steppingstone towards a more comprehensive exploration of the use of ILEs in fostering Systems Thinking and System Dynamics. The insights gained and the recommendations made are prepared to provide some level of guidance for future iterations of this study, but also for wider research efforts aimed at researching the potential of ILEs. The ultimate objective is to foster a more engaging, interactive, and effective learning environment. These findings can therefore play some role in the ongoing discourse on leveraging technology and innovative pedagogical methods and the system dynamics methodology to enhance understanding of the everchanging and complex world we all live in.

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Appendix A:

Model:

Traffic Congestion System Structure

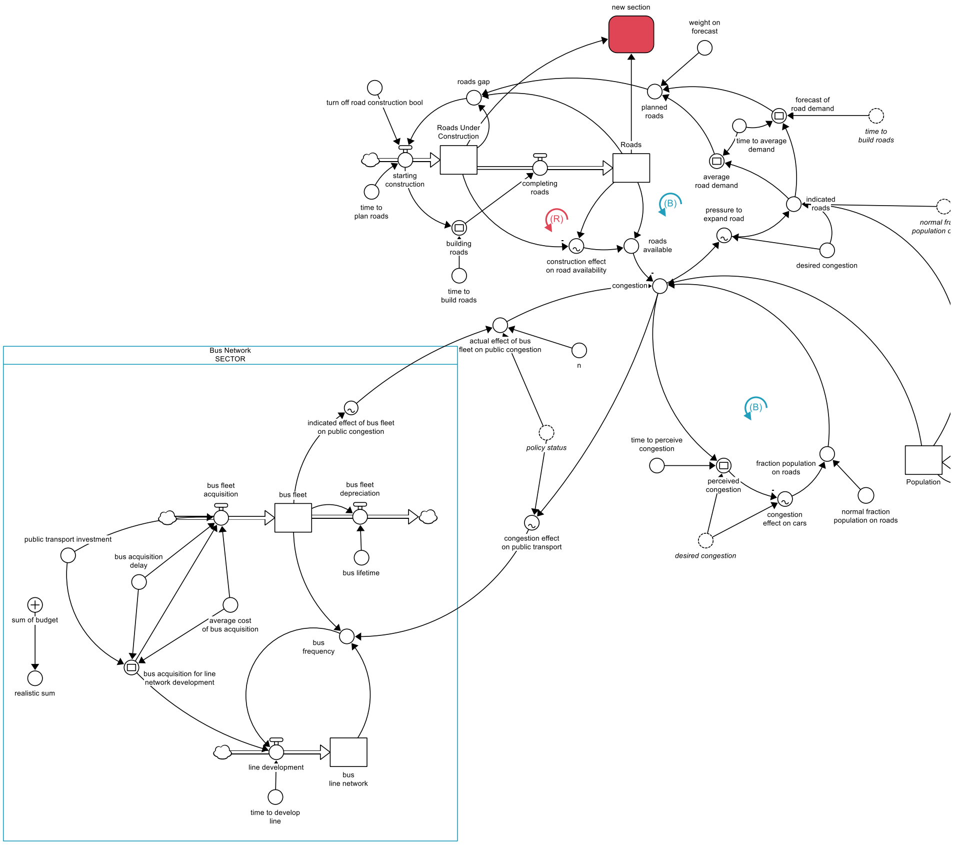

Figure 11 - Traffic Congestion System Structure

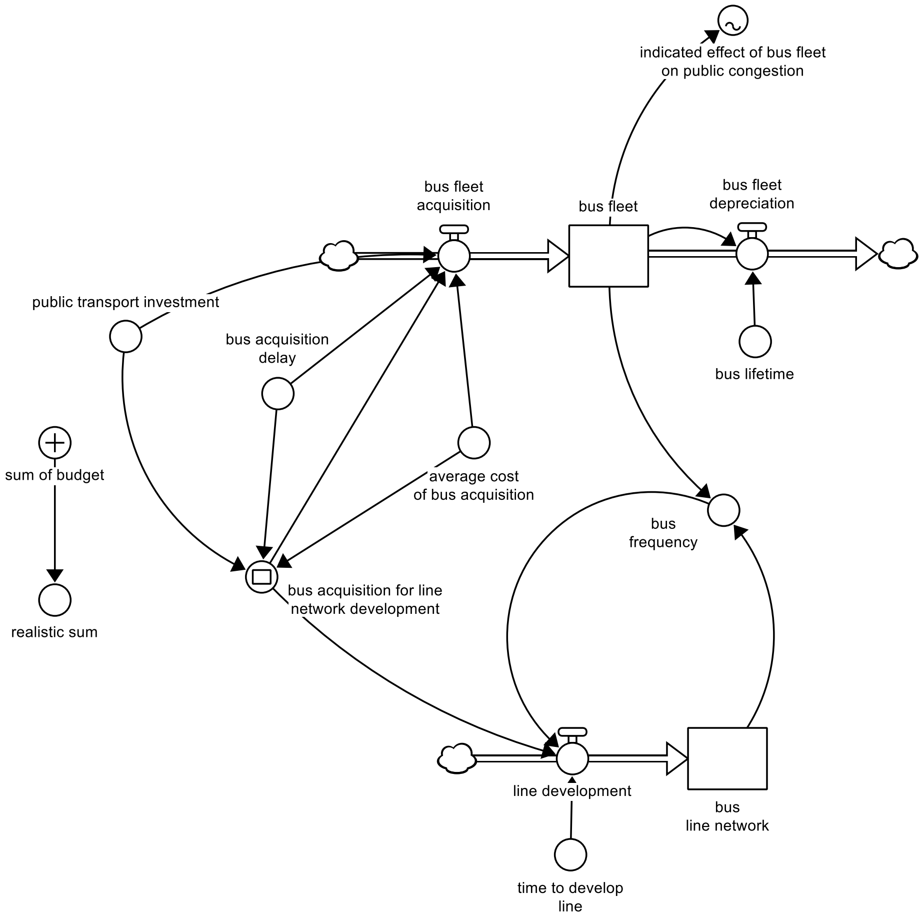

Figure 12 – Bus Network Sector

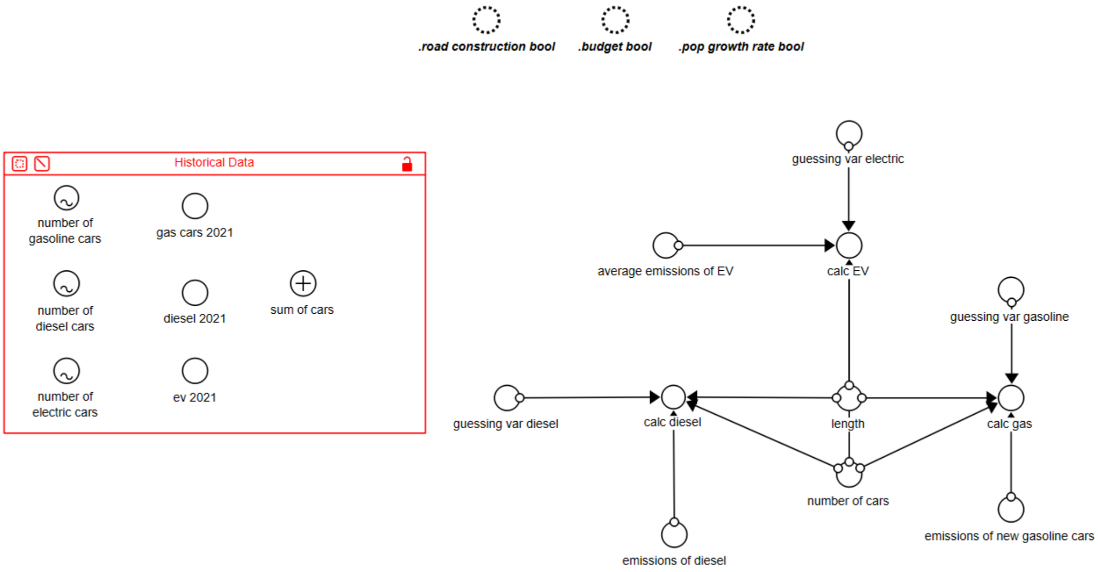

Figure 13 – Some ILE variables

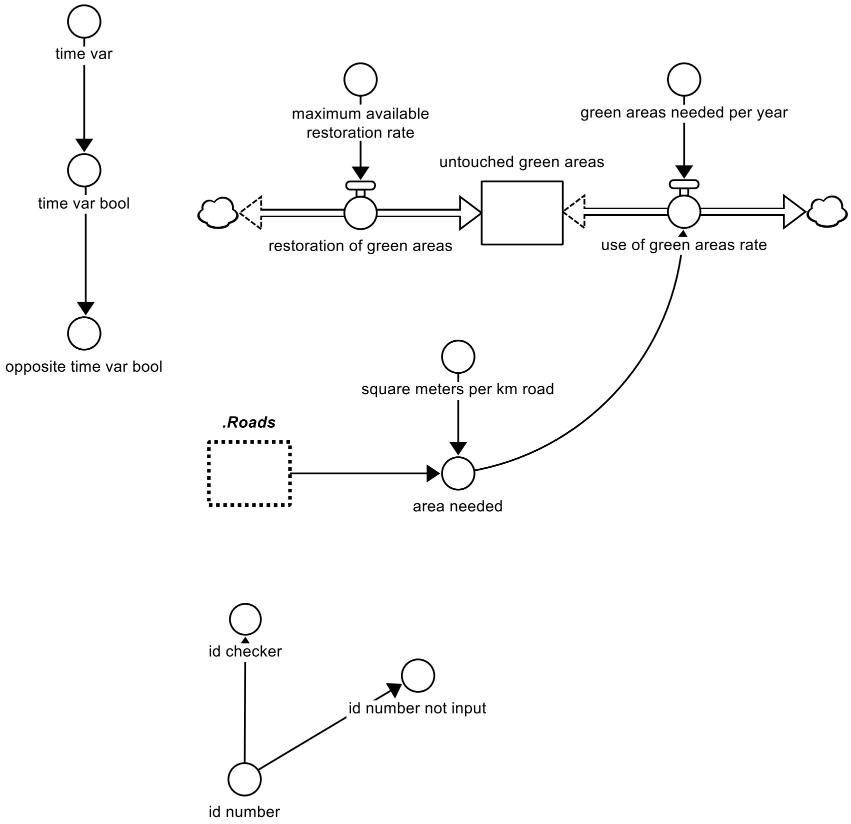

Figure 14 – More structure, both for ILE and for representing Green Areas being used for Road Construction

Model Equations and Specifics:

It should be noted that many of these variables are for ILE-purpose only. All variables with the word “bool” in addition to many others are used to make stuff happen in the ILE.

Variable Name	Equation	Units	Annotation
bus_fleet(t)	bus_fleet(t - dt) + (bus_fleet_acquisition - bus_fleet_depreciation) * dt	bus	NON-NEGATIVE
bus_line_network(t)	bus_line_network(t - dt) + (line_development) * dt	km	NON-NEGATIVE
Population(t)	Population(t - dt) + (changing_population) * dt	people	NON-NEGATIVE
Roads(t)	Roads(t - dt) + (completing_roads) * dt	lane kilometers	NON-NEGATIVE
Roads_Under_Construction(t)	Roads_Under_Construction(t - dt) + (starting_construction - completing_roads) * dt	lane kilometers	NON-NEGATIVE
bus_fleet_acquisition	DELAY1(public_transport_budget//average_cost_of_bus_acquisition; bus_acquisition_delay)+bus_acquisition_for_line_network_development	bus/year	UNIFLOW
bus_fleet_depreciation	bus_fleet/bus_lifetime	bus/year	UNIFLOW
changing_population	population_growth_rate*Population	people/years	
completing_roads	building_roads	lane kilometers/years	UNIFLOW
line_development	DELAY1(bus_acquisition_for_line_network_development//bus_frequency; time_to_develop_line)	km/Years	UNIFLOW
starting_construction	(roads_gap/time_to_plan_roads)* turn_off_road_construction_bool	lane kilometers/years	UNIFLOW
actual_effect_of_bus_fleet_on_public_congestion	SMTH1((indicated_effect_of_bus_fleet_on_public_congestion-1)*policy_status+1; n)	dmnl	
air_traffic	GRAPH(TIME) Points: (2009,00, 54550,1), (2011,00, 62544,1), (2013,00, 64402,7),	dmnl	

	(2015,00, 58293,9), (2016,00, 54731,4), (2017,00, 54270,6), (2018,00, 55905,4), (2019,00, 56986,1), (2020,00, 30174,1), (2021,00, 34918,2)		
air_traffic_2021	34918,2	Tonnes/Co2	
average_cost_of_bus_acquisition	50000	EUR/bus	
average_road_demand	SMTH1(indicated_roads; time_to_average_demand)	lane kilometers	DELAY CONVERTER
budget_bool	public_transport_budget	Dimensionless	
building_roads	DELAY3(starting_construction; time_to_build_roads)	lane kilometers/years	DELAY CONVERTER
bus_acquisition_delay	4	year	
bus_acquisition_for_line_network_development	DELAY1(public_transport_budget/average_cost_of_bus_acquisition; bus_acquisition_delay)	bus/year	DELAY CONVERTER
bus_frequency	(bus_fleet//bus_line_network)*congestion_effect_on_public_transport	bus/km	
bus_lifetime	20	year	
congestion	(fraction_population_on_roads*Population//roads_available) * (actual_effect_of_bus_fleet_on_public_congestion)	people per lane kilometer	
congestion_effect_on_cars	GRAPH(perceived_congestion/desired_congestion) Points: (0,000, 1,323), (0,200, 1,301), (0,400, 1,263), (0,600, 1,211), (0,800, 1,128), (1,000, 1,000), (1,200, 0,767), (1,400, 0,602), (1,600, 0,511), (1,800, 0,474), (2,000, 0,459)	dimensionless	
congestion_effect_on_public_transport	GRAPH(congestion*policy_status) Points: (0,0, 1,800), (5,12820512821, 1,7691913215), (10,2564102564, 1,73677566698), (15,3846153846, 1,70297002702), (20,5128205128, 1,66797691494), (25,641025641, 1,6319843668), (30,7692307692,	Dimensionless	

	1,5951659414), (35,8974358974, 1,55768072027), (41,0256410256, 1,51967330769), (46,1538461538, 1,48127383067), (51,2820512821, 1,44259793895), (56,4102564103, 1,40374680504), (61,5384615385, 1,36480712416), (66,6666666667, 1,32585111427), (71,7948717949, 1,28693651609), (76,9230769231, 1,24810659305), (82,0512820513, 1,20939013133), (87,1794871795, 1,17080143987), (92,3076923077, 1,13234035032), (97,4358974359, 1,09399221707), (102,564102564, 1,05572791727), (107,692307692, 1,01750385078), (112,820512821, 0,979261940234), (117,948717949, 0,94092963097), (123,076923077, 0,902419891084), (128,205128205, 0,863631211404), (133,333333333, 0,8244476055), (138,461538462, 0,784738609678), (143,58974359, 0,744359282983), (148,717948718, 0,703150207199), (153,846153846, 0,660937486848), (158,974358974, 0,617532749193), (164,102564103, 0,572733144231), (169,230769231, 0,526321344702), (174,358974359, 0,478065546082), (179,487179487, 0,427719466586), (184,615384615, 0,375022347168), (189,743589744,		

	0,319698951521), (194,871794872, 0,261459566075), (200,0, 0,2)		
congestion_opposite_bool	1 - desired_congestion_bool	dmnl	
construction_effect_on_road_availability	GRAPH(Roads_Under_Construction/Roads) Points: (0,0000, 1,0000), (0,0500, 0,9627), (0,1000, 0,9340), (0,1500, 0,9091), (0,2000, 0,8867), (0,2500, 0,8656), (0,3000, 0,8444), (0,3500, 0,8282), (0,4000, 0,8133), (0,4500, 0,8008), (0,5000, 0,7934)	dimensionless	
desired_congestion	140	people per lane kilometer	
desired_congestion_bool	IF desired_congestion = 140 THEN 1 ELSE 0	dmnl	
diesel_cars	100	cars	
forecast_of_road_demand	FORCST(indicated_roads; time_to_average_demand; time_to_build_roads)	lane kilometers	DELAY CONVERTER
fraction_population_on_roads	congestion_effect_on_cars*normal_fraction_population_on_roads	dimensionless	
guessing_var_air_traffic	0,1	dmnl	
guessing_var_housing	0,1	dmnl	
guessing_var_road_traffic	0,1	dmnl	
housing_consumption	GRAPH(TIME) Points: (2009,00, 78919,8), (2011,00, 65548,8), (2013,00, 81990,8), (2015,00, 47340,4), (2016,00, 40137,1), (2017,00, 43878,7), (2018,00, 33846,6), (2019,00, 22448,4), (2020,00, 14871,9), (2021,00, 14106)	dmnl	
housing_consumption_2021	34918,2	ton/Co2	
indicated_effect_of_bus_fleet_on_public_congestion	GRAPH(bus_fleet) Points: (1000, 1,0000), (1161,29032258, 0,9117), (1322,58064516, 0,8329), (1483,87096774,	Dimensionless	

	0,7625), (1645,16129032, 0,6996), (1806,4516129, 0,6435), (1967,74193548, 0,5934), (2129,03225806, 0,5486), (2290,32258065, 0,5087), (2451,61290323, 0,4730), (2612,90322581, 0,4411), (2774,19354839, 0,4127), (2935,48387097, 0,3873), (3096,77419355, 0,3646), (3258,06451613, 0,3443), (3419,35483871, 0,3262), (3580,64516129, 0,3101), (3741,93548387, 0,2957), (3903,22580645, 0,2828), (4064,51612903, 0,2713), (4225,80645161, 0,2610), (4387,09677419, 0,2518), (4548,38709677, 0,2437), (4709,67741935, 0,2363), (4870,96774194, 0,2298), (5032,25806452, 0,2240), (5193,5483871, 0,2188), (5354,83870968, 0,2141), (5516,12903226, 0,2100), (5677,41935484, 0,2063), (5838,70967742, 0,2030), (6000, 0,2000)		
indicated_roads	(pressure_to_expand_road*normal_fraction_population_on_roads * Population) // desired_congestion	lane kilometers	
n	1	dmnl	
normal_fraction_population_on_roads	0,7	dimensionless	
opposite_policy_switch_bool	1- policy_switch	Dimensionless	
perceived_congestion	SMTH1(congestion; time_to_perceive_congestion; desired_congestion)	people per lane kilometer	DELAY CONVERTER
planned_roads	(1 - weight_on_forecast)*average_road_demand + weight_on_forecast*forecast_of_road_demand	lane kilometers	
policy_adj_time	policy_time_period/3	years	
policy_deadline	2050	years	

policy_start_time	2021	years	
policy_status	IF TIME>policy_start_time AND policy_switch=1 THEN 1 ELSE 0	dmnl	
policy_switch	1	dmnl	
policy_time_period	policy_deadline-policy_start_time	years	
pop_growth_rate_bool	IF (population_growth_rate = population_assist_bool) THEN 0 ELSE 1	dmnl	
pop_opposite_bool	1 - pop_growth_rate_bool	dmnl	
population_assist_bool	HISTORY(population_growth_rate; 0)	per year	
population_growth_rate	0,025	per year	
pressure_to_expand_road	GRAPH(congestion//desired_congestion) Points: (0,000, 0,000), (0,200, 0,02526), (0,400, 0,08682), (0,600, 0,2331), (0,800, 0,5352), (1,000, 1,000), (1,200, 1,465), (1,400, 1,767), (1,600, 1,913), (1,800, 1,975), (2,000, 2,000)	dimensionless	
public_transport_budget	1000000	EUR/year	
realistic_sum	(sum_of_budget*10) * 2	EUR	
road_construction_bool	1 - turn_off_road_construction_bool	dmnl	
road_traffic	GRAPH(TIME) Points: (2009,00, 152064,4), (2011,00, 152064,4), (2013,00, 152064,4), (2015,00, 152064,6), (2016,00, 148029,6), (2017,00, 137281,7), (2018,00, 144250), (2019,00, 144152,1), (2020,00, 147163,7), (2021,00, 164786,2)	ton/co2	
road_traffic_2021	164786,2	cars	
roads_available	construction_effect_on_road_availability*Roads	lane kilometers	

roads_gap	MAX(planned_roads - (Roads_Under_Construction + Roads); 0)	lane kilometers	
sum_of_budget	public_transport_budget	EUR	SUMMING CONVERTER
time_to_average_demand	5	years	
time_to_build_roads	10	years	
time_to_develop_line	4	years	
time_to_perceive_congestion	1	years	
time_to_plan_roads	3	year	
turn_off_road_construction_bool	1	Dimensionless	
weight_on_forecast	0,5	dimensionless	
ønsket_tid_i_trafikk	GRAPH(desired_congestion) Points: (0,0, 0,00), (20,0, 2,00), (40,0, 4,00), (60,0, 6,00), (80,0, 8,00), (100,0, 10,00), (120,0, 12,00), (140,0, 14,00), (160,0, 16,00), (180,0, 18,00), (200,0, 20,00)	dmnl	
average_emissions_of_EV	44	g/Co2/km	
calc_diesel	(guessing_var_diesel * (emissions_of_diesel*length)) * number_of_cars	Grams/co2	
calc_EV	(guessing_var_electric*(average_emissions_of_EV*length)) * number_of_cars	Grams/co2	
calc_gas	(guessing_var_gasoline * (length*emissions_of_new_gasoline_cars)) * number_of_cars	Grams/co2	
diesel_2021	34303	cars	
emissions_of_diesel	231	g/Co2/km	

emissions_of_new_gasoline_cars	241	g/Co2/km	
ev_2021	35108	cars	
gas_cars_2021	35892	cars	
guessing_var_diesel	0,1	Dimensionless	
guessing_var_electric	0,1	dmnl	
guessing_var_gasoline	0,1	dmnl	
length	1	km	
number_of_cars	1000	cars	
number_of_diesel_cars	GRAPH(TIME) Points: (2008,00, 29434), (2009,00, 33854), (2010,00, 32982), (2011,00, 37827), (2012,00, 41568), (2013,00, 44413), (2014,00, 46085), (2015,00, 46863), (2016,00, 45932), (2017,00, 44176), (2018,00, 41532), (2019,00, 39323), (2020,00, 37062), (2021,00, 34303)	cars	GF EXTRAPOLATED
number_of_electric_cars	GRAPH(TIME) Points: (2008,00, 149), (2009,00, 166), (2010,00, 144), (2011,00, 244), (2012,00, 582), (2013,00, 1499), (2014,00, 3604), (2015,00, 6716), (2016,00, 9392), (2017,00, 12764), (2018,00, 17208), (2019,00, 21888), (2020,00, 27337), (2021,00, 35108)	cars	GF EXTRAPOLATED
number_of_gasoline_cars	GRAPH(TIME) Points: (2008,00, 76334), (2009,00, 73918), (2010,00, 69579), (2011,00, 66381), (2012,00, 64384), (2013,00, 62269), (2014,00, 59930), (2015,00, 58118), (2016,00, 52061), (2017,00, 48998), (2018,00, 45551), (2019,00, 43036), (2020,00, 39312), (2021,00, 35892)	cars	GF EXTRAPOLATED

sum_of_cars	number_of_diesel_cars + number_of_electric_cars + number_of_gasoline_cars	cars	SUMMING CONVERTER
untouched_green_areas(t)	untouched_green_areas(t - dt) + (restoration_of_green_areas - use_of_green_areas_rate) * dt	Square Kilometers	NON-NEGATIVE
restoration_of_green_areas	maximum_available_restoration_rate	Square Kilometers/years	
use_of_green_areas_rate	area_needed*green_areas_needed_per_year	Square Kilometers/years	
area_needed	.Roads*square_meters_per_km_road	Kilometers^3*lane	
bus_carbon_intensity_by_deadline	0	gram*CO2eq/(passenger*km)	
bus_emissions	bus_emissions_per_km	ton*CO2eq/year	
bus_emissions_per_km	IF policy_status=1 THEN HISTORY(historical_bus_carbon_intensity_in_gram; policy_start_time)/gram_per_ton +RAMP((bus_carbon_intensity_by_deadline-HISTORY(historical_bus_carbon_intensity_in_gram; policy_start_time))/gram_per_ton /policy_time_period; policy_start_time; policy_deadline) ELSE MAX(0; historical_bus_carbon_intensity_in_gram/gram_per_ton)	ton*CO2eq/(passenger*km)	
car_emissions	car_emissions_per_km	ton*CO2eq/year	
car_emissions_per_km	IF switch1=1 THEN future_car_carbon_intensity_in_gram/gram_per_ton ELSE historical_car_carbon_intensity_in_gram/gram_per_ton	ton*CO2eq/(passenger*km)	
carbon_intensity_of_energy_consumption	carbon_intensity_of_energy_consumption_in_grams/gram_per_ton	ton*CO2eq/kWh	
carbon_intensity_of_energy_consumption_in_grams	IF policy_status=1 THEN future_housing_carbon_intensity ELSE 150	gram*CO2eq/kWh	

decentralized_housing_energy_consumption	pc_housing_energy_consumption	kWh/year	
emissions	housing_emissions+road_passenger_transport_emissions	ton*CO2eq/year	
future_car_carbon_intensity_in_gram	GRAPH(TIME) Points: (2020,00, 168,0), (2025,00, 153,0), (2030,00, 138,0), (2035,00, 122,0), (2040,00, 107,0), (2045,00, 92,0), (2050,00, 77,0)	gram*CO2eq/(passenger*km)	
future_housing_carbon_intensity	GRAPH(TIME) Points: (2020,00, 150,0), (2025,00, 150,0), (2030,00, 150,0), (2035,00, 150,0), (2040,00, 150,0), (2045,00, 150,0), (2050,00, 150,0)	gram*CO2eq/kWh	
future_pc_housing_energy_consumption	GRAPH(TIME) Points: (2020,00, 18000), (2025,00, 18000), (2030,00, 18000), (2035,00, 18000), (2040,00, 18000), (2045,00, 18000), (2050,00, 18000)	kWh/year/people	
gram_per_ton	1000000	gram/ton	
green_areas_needed_per_year	0,2	Square Kilometers	
historical_bus_carbon_intensity_in_gram	GRAPH(TIME) Points: (2015,000, 80,00), (2016,000, 77,9996334311), (2017,000, 76,000030188), (2018,000, 73,999969812), (2019,000, 72,0003665689), (2020,000, 70)	gram*CO2eq/(passenger*km)	GF EXTRAPOLATED
historical_car_carbon_intensity_in_gram	GRAPH(TIME) Points: (2015,000, 183,00), (2016,250, 179,30), (2017,500, 175,50), (2018,750, 171,80), (2020,000, 168,00)	gram*CO2eq/(passenger*km)	GF EXTRAPOLATED
housing_emissions	carbon_intensity_of_energy_consumption*decentralized_housing_energy_consumption	ton*CO2eq/year	
id_number	0	dmnl	
id_number_not_input	id_number	dmnl	

maximum_available_restoration_rate	0,002	Dimensionless	
modulo_checker	IF id_number = 874 OR id_number = 345 OR id_number = 615 OR id_number = 901 OR id_number = 725 OR id_number = 433 OR id_number = 290 OR id_number = 198 OR id_number = 673 OR id_number = 410 OR id_number = 766 OR id_number = 177 OR id_number = 592 OR id_number = 663 OR id_number = 562 OR id_number = 231 OR id_number = 247 OR id_number = 681 OR id_number = 719 OR id_number = 529 OR id_number = 136 OR id_number = 379 OR id_number = 220 OR id_number = 880 OR id_number = 487 OR id_number = 904 OR id_number = 487 OR id_number = 371 OR id_number = 988 OR id_number = 555 OR id_number = 420 THEN 1 ELSE 0	dmnl	
opposite_time_var_bool	1 - time_var_bool	dmnl	
pc_housing_energy_consumption	IF policy_status=1 THEN future_pc_housing_energy_consumption ELSE 18000	kWh/year/people	
policy_deadline	2050	years	
policy_start_time	2020	years	
policy_status	100	dmnl	
policy_time_period	100	years	
road_construction_carbon_intensity_in_gram	1733	gram*CO2eq	
road_emissions_per_km	(road_construction_carbon_intensity_in_gram/gram_per_ton) * .Roads_Under_Construction	CO2eq*Kilometers*lane*Tons	
road_passenger_transport_emissions	bus_emissions+car_emissions	ton*CO2eq/year	
square_meters_per_km_road	2	Square Kilometers	
switch1	0	dmnl	

time_var	TIME	years	
time_var_bool	IF time_var = STOPTIME THEN 1 ELSE 0	dmnl	

Table 20 – Equations from Model

Total	**Count**	**Including Array Elements**
Variables	132	132
Modules	2	
Sectors	3	
Stocks	6	6
Flows	8	8
Converters	118	118
Constants	48	48
Equations	78	78
Graphicals	17	17
Macro Variables	52	

Table 21 – Graph depicting different types of variables

Run Specs	
Start Time	2000
Stop Time	2050
DT	1/8
Fractional DT	True
Save Interval	0,125
Sim Duration	5
Time Units	years
Pause Interval	0
Integration Method	Euler
Keep all variable results	True

Run By	Run
Calculate loop dominance information	False

Table 22 – Run Specifications

Appendix B:

Multivariate Analysis Parameter Values:

In the multivariate analysis described in the methodology section, 30 runs were performed in which the three parameters Population Growth Rate, Desired Congestion and Public Transport Investment were used. Below, the values combined is presented.

Run ID	**Population Growth Rate**	**Desired Congestion**	**Public Transport Investment**
Type of Distribution:	**Uniform**	**Unfiform**	**Incremental**
Run 1	0	100	1000000
Run 2	-0,025	150	2000000
Run 3	0,025	50	3000000
Run 4	-0,0125	125	4000000
Run 5	0,0375	25	5000000
Run 6	-0,0375	75	6000000
Run 7	0,0125	175	7000000
Run 8	-0,01875	62,5	8000000
Run 9	0,03125	162,5	9000000
Run 10	-0,04375	112,5	10000000
Run 11	0,00625	12,5	1000000
Run 12	-0,03125	187,5	2000000
Run 13	0,01875	87,5	3000000
Run 14	-0,00625	37,5	4000000
Run 15	0,04375	137,5	5000000
Run 16	-0,003125	168,75	6000000
Run 17	0,046875	68,75	7000000
Run 18	-0,028125	18,75	8000000
Run 19	0,021875	118,75	9000000
Run 20	-0,040625	93,75	10000000
Run 21	0,009375	193,75	1000000
Run 22	-0,015625	143,75	2000000
Run 23	0,034375	43,75	3000000
Run 24	-0,034375	106,25	4000000
Run 25	0,015625	6,25	5000000
Run 26	-0,009375	56,25	6000000
Run 27	0,040625	156,25	7000000
Run 28	-0,021875	31,25	8000000
Run 29	0,028125	131,25	9000000
Run 30	-0,046875	181,25	10000000

Table 23 – Values of parameters for the multivariate sensitivity analysis